BLOOD BANK ANALYSIS

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THESIS

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ABSTRACT

Blood bank operations of various hospitals in the Monterey area and the Red Cross Center in San Jose were studied, and as a result a simulation model is developed which is used to determine the effects on shortages and outdating of various operating policies in a given blood bank. Data from Fort Ord Hospital is used to illustrate the model. Specific results are discussed for a single blood type (A+), but the model can be used for all blood types. The model illustrates the difficulty of reducing both shortages and outdating simultaneously, but shows where this might be possible if certain operating policies are instituted.

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Personnel at Ft. Ord Hospital, the Red Cross Center, San Jose, and Monterey Hospital, Ltd. were extremely helpful in our data collection effort and we greatly appreciate the assistance which they so willingly gave.

I. INTRODUCTION

Over five million units of whole blood are transfused in the United States annually. To maintain an adequate supply of whole blood, hospitals may establish their own collection facilities, purchase the amount needed from commercial banks, participate in the Red Cross program or operate under a combination of these various policies. This paper will discuss the blood banking procedures, point out common problem areas and indicate, under certain specified conditions, alternate policies that may be employed to reduce inefficiency. Other work in this area is summarized in Chapter II (entitled Blood Bank Inventory Control) of reference [1].

The shelf life of a unit of whole blood is limited by law to 21 days. Whole blood that is older than 21 days is referred to as outdated blood. Outdated blood can be used to produce other components such as plasma, but it cannot be used for whole blood transfusions. In this sense, outdating is considered as a loss because it diminishes the available supply of whole blood.

The problem of outdating is complicated by the variability of both supply and demand. The variability in supply can be reduced by scheduling donors. Scheduling operations can help reduce the variability of demand, but because emergency requests for blood often arise, facilities may find themselves short of one type of blood, while several units of another type are becoming outdated.

In addition, processing, storage and transportation of whole blood is expensive. Reduced inventories lower cost but increase the possibility

of shortages due to inadequate supplies. Higher inventory levels insure proper supply, but are costly because of increased outdating.

Human blood is classified into four main groups: A, B, AB, and O. Each group is divided into two types, RH positive and RH negative. Over 70 percent of all blood is either A positive or O positive. The results presented in this paper are applicable to all blood types; however, it should be noted that distributional assumptions are based on data pertaining to the more common blood groups.

II. CHARACTERISTICS OF LOCAL BLOOD BANKING FACILITIES

Three types of blood banking facilities are found in the Monterey area. The Silas B. Hays Hospital at Ft. Ord operates independently of the Red Cross and other blood sources by processing and using blood obtained from its own donors. If a shortage should occur, the hospital obtains amounts needed from the Red Cross.

The Central California Red Cross Blood Center located in San Jose supplies blood to over 30 hospitals, including those in the Monterey-Salinas area. While all the blood is processed at the Red Cross Center, most of the inventory is located at the member hospitals. Monterey Hospital Ltd. is the third type of facility in the Monterey area. It relies almost totally on the Red Cross for its blood supply. Discussions with personnel at these three facilities indicate that improvements could be made in the following areas.

A. HOSPITAL INTERACTION

Increased interaction between hospitals will tend to reduce outdating simply by expanding the demand for blood. If one hospital has a relatively fresh, but limited supply of A+ and several units are scheduled for

transfusion, older units from another hospital with a few scheduled transfusions could be used. In a sense, hospitals would be pooling their blood resources and combining their demands in an effort to reduce outdating. Ft. Ord and Monterey Ltd. have very limited contact with other hospitals. Blood that is close to becoming outdated can be turned into the Red Cross by member hospitals and an effort is made to redistribute this blood before it outdates, but records show that even this procedure still results in a relatively high outdating rate. Hospitals tend to hold their blood supplies until just prior to outdating, thus reducing the effect of a redistribution policy. Although there may be periods when everyone has too much blood on hand and even combining demands will not significantly decrease outdating, we feel that increased interaction between hospitals can help reduce the problem.

B. INVENTORY LEVELS

We determined that most blood bank inventory levels seem to be established the same way: by experience. Past data is rarely used to determine these levels and little if any statistical analysis is performed.

C. EXISTING RECORDS

We feel that the main reason past data is not used, is due to the way in which it is recorded. Every unit of blood that is processed is recorded, somewhere. But information giving the number of units by type that are crossmatched and eventually used; crossmatched and not used; not crossmatched; obtained from outside sources and used; or obtained from outside sources and not used, is simply not recorded. These quantities can be determined by tracing each unit of blood through the several forms that record its history, but speaking from experience, this is a very

tedious and time-consuming job. Ft. Ord and the Red Cross both record each unit of blood processed on a variety of forms, but these records are not directly applicable in determining stockage levels. Monterey Ltd. keeps very few records because its blood is supplied by the Red Cross and the Red Cross maintains most of the records concerning blood used at member hospitals. At present, existing records do not provide information in the form required to assist in determining optimum stockage levels.

D. DEMAND WITHOUT USAGE

Another issue, and one that will receive analytical attention later, is that of demand rates greatly exceeding usage rates. The problem is common at every hospital, and we feel that it is the driving force that results in high outdating losses. In order to insure that blood is readily available if needed, doctors will request a great deal more blood than is actually used. Anywhere from two to five times as much blood will be demanded than is actually transfused. This "safety factor" causes a great deal of blood to be lost through outdating. Hospital blood banks must stock to cover these demand rates. It is not unusual for a unit of blood to be crossmatched and sent to surgery several times during a three-week period, only to finally become outdated because it was never transfused. It will be shown that a reduction in this "safety factor" would significantly reduce outdating.

E. INVENTORY POLICIES

Whenever possible, the oldest blood in the inventory should be used first. For some types of surgery fresh blood (blood drawn very recently) is required and a strict First In First Out (FIFO) policy cannot be followed. Blood that is requested, crossmatched, and sent to surgery is not

available for use until it is sent back from surgery, thus making a FIFO policy even more difficult to follow. The opposite extreme would be a Last In First Out (LIFO) policy which would cause the freshest blood always to be used first. Most hospitals fall somewhere between these two extremes, and for this reason, both policies will be analyzed to indicate upper and lower bounds on various inventory policies.

F. COST OF OUTDATING AND SHORTAGES

Both outdating and shortages are unwanted quantities in any blood banking system. Unfortunately, it is very difficult to determine the cost of either one. Outdated blood cannot be used for whole blood transfusions, but it can be broken down into components that do have usefulness under certain circumstances. In addition, for 21 days the outdated blood was available if needed; therefore, the cost of outdating should not be equated to total processing costs. Shortages force banks to go to outside sources and are, in that sense, costly. Shortages may also force the delay of scheduled operations, thus endangering human life. As pointed out earlier, reduced outdating may lead to increased shortages and reduced shortages may tend to increase outdating. A policy that minimizes both is obviously desired. Before attempting to obtain an optimum policy, a good understanding of how blood moves through a banking system is required.

III. SIMPLE DETERMINISTIC MODEL

We felt that the initial model should describe the flow of blood through a banking facility, but that it should also be a relatively simple model. A deterministic model based on one-week time periods and representing one type of blood will be presented. Constant inputs and outputs

are assumed. The flow of blood will be illustrated by the use of block diagrams. Later, the model becomes more complex when input parameters are assumed to be random variables and alternate inventory policies with various safety factors are analyzed.

A. MODEL DEVELOPMENT

To describe the flow of blood through a banking system, several inputs and outputs must be specified. The following notation is used in the remainder of the paper:

I_i = Internal input in time period i

S_i = External input in time period i

O_i = Amount oudated in time period i

D_i = Amount demanded in time period i

R_i = Amount used in time period i

V_{ij}= Surplus from period i, j periods old

a_i = Ratio of demand to usage for period i

To illustrate this notation, the flows of a given blood type in a typical time period of one week are shown in figure 1.

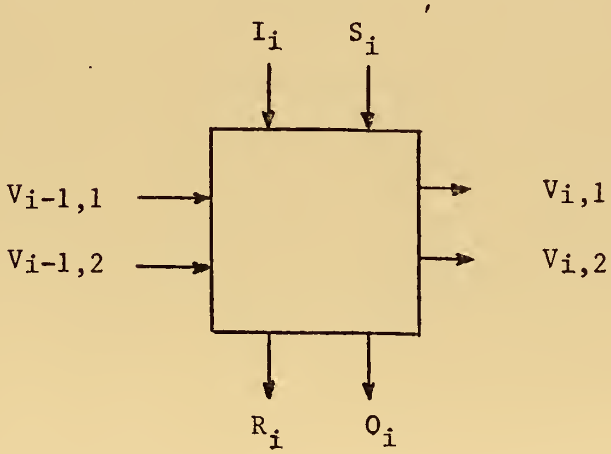
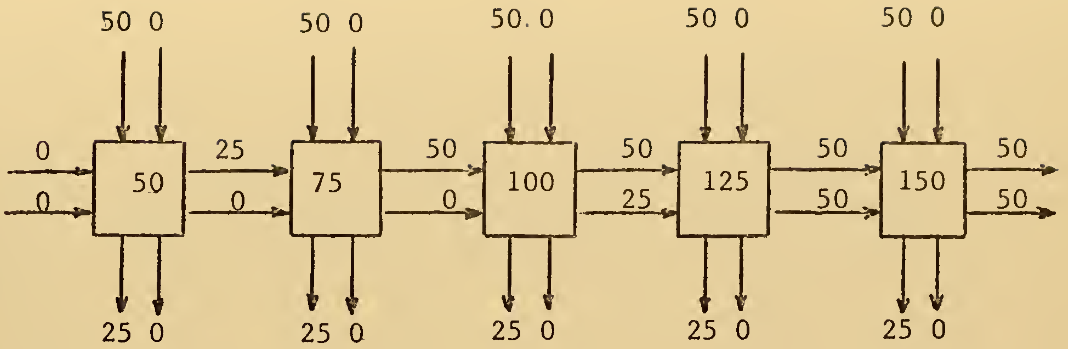


Fig. 1. Blood Flows in Period i

During the i^{th} week the blood bank receives blood from donors (I_i), blood from external sources (S_i) and blood from the previous week that is one ($V_{i-1,1}$) or two ($V_{i-1,2}$) weeks old. Blood that is three weeks old is outdated ($O_i = V_{i-1,3}$) and is therefore represented as an output. Blood that is transfused (R_i) is also an output. Surplus blood from the i^{th} week that is one ($V_{i,1}$) or two ($V_{i,2}$) weeks old is available for use in the $i^{th}+1$ week. Several of these time periods can be used to describe the flow of blood through a banking system. Because this is a very basic model, several simplifying assumptions are made. Only a single type of blood is represented; time periods are one week long; and values of I, R, and a are fixed for each example. The type of inventory policy (LIFO or FIFO) is also fixed and blood from outside sources is assumed to be as fresh as blood from internal sources. Inputs and outputs are determined for each time period until a steady state condition is reached. By way of illustration, three examples of flow diagrams will be presented. Initial values for $V_{i-1,1}$ and $V_{i-1,2}$ are assumed to be zero. The numbers appearing inside each time period are inventory levels for that week and must be greater than or equal to a_iR_i which is the total demand for that period. If I_i is less than a_iR_i, then S_i will be greater than zero. In other words, if the demand exceeds the supply from internal sources, then blood must be obtained from external sources. The information below each example gives the type of inventory policy assumed, values for a, I and R and steady state values for S_i, O_i and inventory levels. In examples two and three, steady state is reached when a three-week cycle is established. It should be noted that cycles appear in several of the flow diagrams.

Example 1

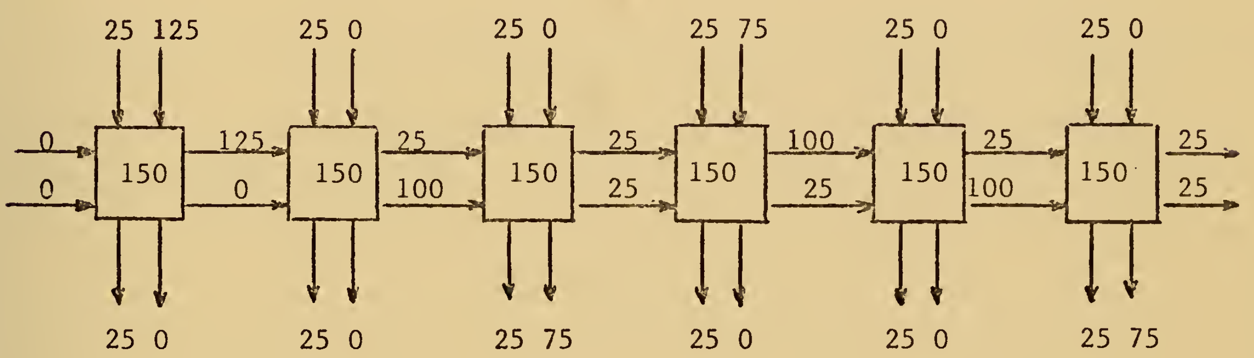


FIFO Policy

Initial Values: a = 2, I = 50, R = 25

Steady State Values: S_i = 0, O_i = 25, Inventory = 150

Example 2

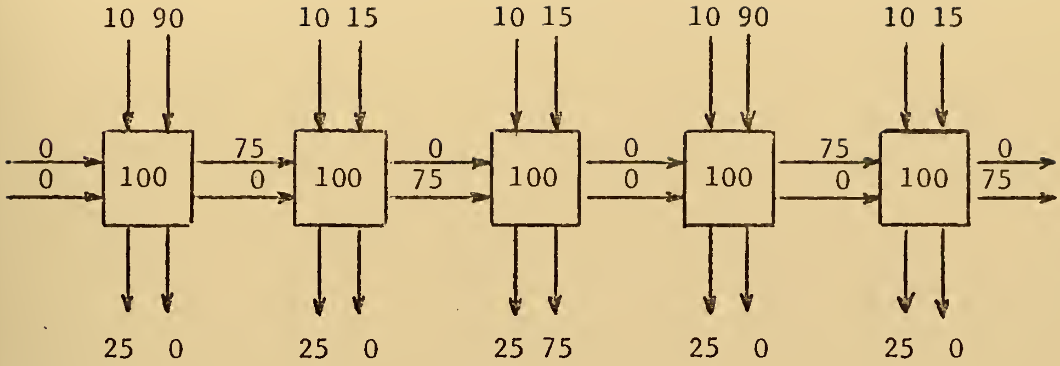


FIFO Policy

Initial Values: a = 6, I = 25, R = 25

Steady State Values: S_i cycle, 0 - 0 - 75, O_i cycle, 0 - 75 - 0,
Inventory = 150

Example 3



LIFO Policy

Initial Values: a = 4, I = 10, R = 25

Steady State Values: S_i cycle 90 - 15 - 15, O_i cycle 0 - 0 - 75,
Inventory = 100

With this basic understanding of how blood moves through a banking facility, several relationships can now be developed using the notation of this deterministic model.

IV. BASIC RELATIONSHIPS

Expressions for S_i and D_i are the same regardless of the type of inventory policy employed. These are developed first. We assume that blood banks will not require blood from outside sources unless the demand exceeds the amount on hand. This is expressed as follows:

If $D_i \leq I_i + V_{i-1,1} + V_{i-1,2}$, then $S_i = 0$

If $D_i > I_i + V_{i-1,1} + V_{i-1,2}$ then $S_i = D_i - (I_i + V_{i-1,1} + V_{i-1,2})$.

Blood banks will obtain blood from outside sources to meet demands.

Thus

$$S_i = \max\ (\ 0,\ D_i - (I_i + V_{i-1,1} + V_{i-1,2})\ ). \qquad (1)$$

As mentioned before, doctors request more blood than is actually transfused, thus inserting a safety factor (a) into the system. The demand for blood is related to actual usage as follows:

$$D_i = a_i R_i . \tag{2}$$

By setting inputs equal to outputs in Fig. 1, we can obtain,

$$V_{i-1,1} + V_{i-1,2} + I_i + S_i = R_i + O_i + V_{i,1} + V_{i,2} . \tag{3}$$

The next step is to look at what relationships are established when a specific inventory policy is followed. Assuming that the oldest blood will be used first (FIFO), equations for O_i, $V_{i,1}$ and $V_{i,2}$ are as follows:

If $R_i \leq V_{i-1,2}$ then $O_i = V_{i-1,2} - R_i$.

If $R_i > V_{i-1,2}$ then $O_i = 0$.

Thus $O_i = \max (0, V_{i-1,2} - R_i)$. (4)

If $R_i < V_{i-1,1} + V_{i-1,2}$ then $V_{i,1} = I_i + S_i$.

If $R_i \geq V_{i-1,1} + V_{i-1,2}$ then $V_{i,1} = I_i + S_i - (R_i - V_{i-1,1} - V_{i-1,2})$.

Thus $V_{i,1} = I_i + S_i - \max (0, R_i - (V_{i-1,1} + V_{i-1,2}))$. (5)

If $R_i \leq V_{i-1,2}$ then $V_{i,2} = V_{i-1,1}$.

If $V_{i-1,1} + V_{i-1,2} \geq R_i > V_{i-1,2}$ then $V_{i,2} = V_{i-1,1} - (R_i - V_{i-1,2})$

If $R_i > V_{i-1,1} + V_{i-1,2}$ then $V_{i,2} = 0$.

Thus $V_{i,2} = \max (0, V_{i-1,1} - \max (0, R_i - V_{i-1,2}))$. (6)

Following the same reasoning, we can develop like expressions when it is assumed that the freshest blood is used first (LIFO policy).

In this case

$$O_i = V_{i-1,2} - \max (0, R_i - I_i - S_i - V_{i-1,1}), \tag{7}$$

$$V_{i,1} = \max (0, I_i + S_i - R_i), \tag{8}$$

$$V_{i,2} = \max (0, V_{i-1,1} - \max (0, R_i - I_i - S_i)). \tag{9}$$

Thus for a given inventory policy and known values for R_i, and I_i, O_i, $V_{i,1}$ $V_{i,2}$ and S_i can be determined. As mentioned before, a major

problem area in blood banking operations is the variability of supply and demand. Therefore, the next step will be to assume that I_i and R_i are random variables with known distributions. A sequence of realizations of these internal inputs and requirements will determine the performance of the system.

V. ANALYTIC PROBABILITY APPROACH

The independent random variables which drive the blood banking system are the internal input I_i and requirements R_i for each period i. Assume these have distribution functions

$$A(x) = P\left[I_i \leq s\right], \; x \geq 0 \quad i = 1, 2, \ldots,$$

$$B(x) = P\left[R_i \leq x\right], \; x \geq 0 \quad i = 1, 2, \ldots,$$

and assume that the $\{I_i\}$ are independent, the $\{R_i\}$ are independent and each sequence is independent of the other. Even with these somewhat stringent requirements it will be seen that an analytic approach soon becomes intractable, and that a simulation model must be used.

Let $C(x) = P\left[0_i \leq x\right]$, be the distribution function for the amount of outdated blood in period i. Assume we have reached steady state (and that no cycles exist as did in the deterministic models).

Recall from (4) for a FIFO policy that $0_i = \max(0, V_{i-1,2} - R_i)$. For $x > 0$ $P\left[0_i \leq x\right] = P\left[V_{i-1,2} - R_i \leq x\right]$, and from our assumptions, $V_{i-1,2}$ and R_i are independent. Thus if

$$P\left[V_{i-1,2} \leq x\right] = F(x)$$

then

$$P\left[0_i \leq x\right] = \int_0^\infty F(x + u)\, dB(u).$$

However, F is an unknown distribution which in turn depends on A and B. Since we are assuming steady state conditions, $V_{i-1,2}$ And $V_{i,2}$ have

the same marginal distribution, and $V_{i,2}$ is given by (6) for a FIFO policy. It is a function of both $V_{i-1,1}$ and $V_{i-1,2}$. From (5) we see that $V_{i,1}$ is also a function of these random variables, so that $V_{i,1}$ and $V_{i,2}$ are not independent. Thus, $V_{i-1,1}$ and $V_{i-1,2}$ are not independent by the same reasoning. Therefore, we have little hope of getting further in this line of approach to determine the distribution of O_i. Similar difficulties are encountered in trying to determine the moments of O_i. In the next section we discuss the results of a simulation model based on the equations in section IV and using distributions A and B determined from internal supply and requirements at the Ft. Ord Hospital.

VI. SIMULATION APPROACH

The relationships developed in section IV and the distributions A(x) and B(x) are the basis of a simulation model which is described in this section. The distributions A(x) and B(x) are determined from data obtained at Ft. Ord Hospital. Initially, the simulation generates values for I_i and R_i from these distributions. (It should be noted that any distributions can be used for A and B, including degenerate ones.) Using these values, the simulation computes $V_{i,1}$, $V_{i,2}$, S_i and O_i for values of a_i from 1 through 5. The equations developed previously are used to compute these values for both FIFO (equations (1) - (6)) and LIFO (equations (1) - (3) and (7) - (9)) policies. The results are recorded and the procedure is repeated for a predetermined number of weeks. Blood bank operations were simulated for various periods of time (up to six years) until it was determined that three years or 156 weeks produced steady state results.

VII. VERIFICATION OF RESULTS

One very important step in any computer simulation is verification of the model for both internal consistency and for validity when results are checked against real data. Initially our model was checked for consistency by using deterministic inputs for I_i and R_i and checking the output against the results obtained from the deterministic model in section III. These results checked out exactly and we were then ready to compare simulation results against actual blood bank data.

As mentioned before, data on blood bank operations is usually not available in format that is readily applicable to statistical analysis. The data used for verification of the simulation was obtained from the Ft. Ord Hospital. The data base consists of 2988 units of blood that were processed by the Ft. Ord blood bank during 1971. Weekly values for I_i and R_i were obtained for each blood type. Information on the number of units that were obtained from outside sources and the number of units that became outdated was also recorded.

In Figures 2 and 3 $P\left[I_i \geq x\right]$ and $P\left[R_i \geq x\right]$ are plotted on semilogarithmic paper for A+ blood. For clarity only A+ blood data is analyzed in the body of the paper. Graphs and data for the remaining blood types are found in Appendix A. From these plots, it seems reasonable to assume that both I_i and R_i are geometrically distributed with different means. That is,

$$P\left[I_i \geq x\right] = q_1^{x}, \; x = 0, 1, 2, \ldots$$

$$P\left[R_i \geq x\right] = q_2^{x}, \; x = 0, 1, 2, \ldots$$

The fitted lines are obtained by first calculating an estimate of the expected value for I_i and R_i from the average of the data. For A+ blood

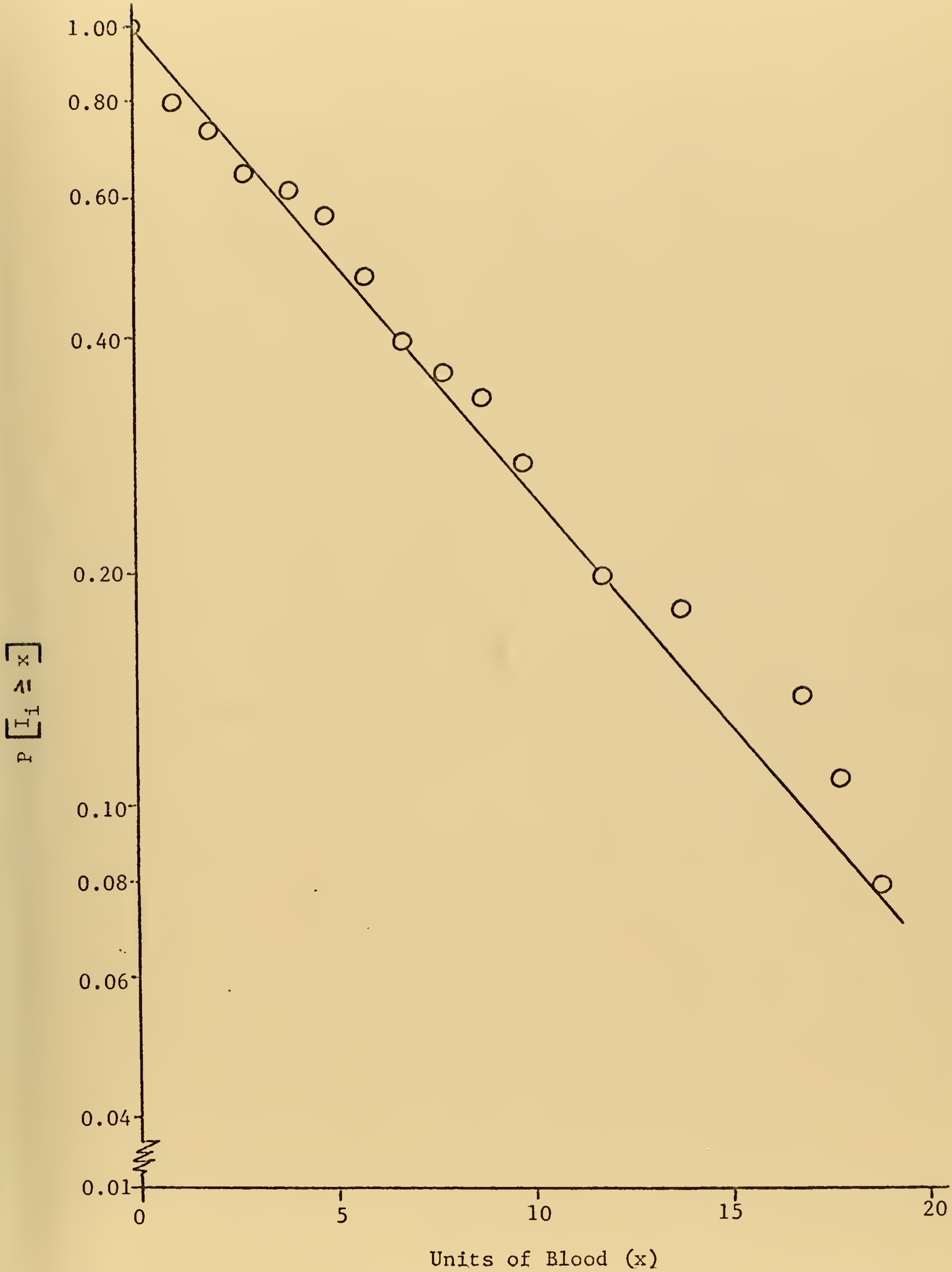


Fig. 2 Distribution of A+ Blood Internally Supplied at Fort Ord, FY71.

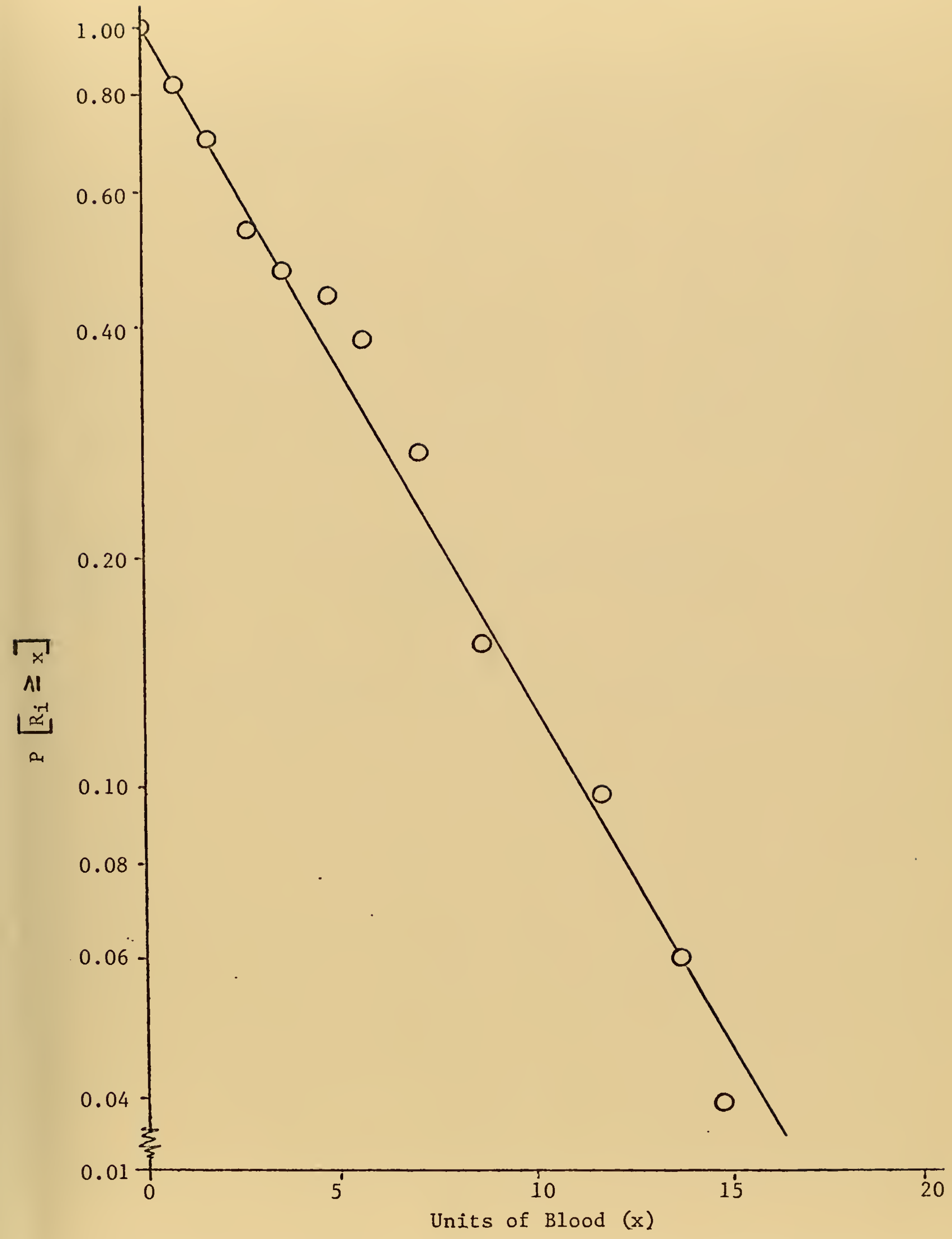


Fig. 3 Distribution of A+ Blood Transfused at Fort Ord, FY71.

BLOOD TYPE	INPUT DATA	TIME PERIOD
A+	Q INTERNAL =.871605 Q REQUIRED =.814947	156 WEEKS

SIMULATION RESULTS

POLICY	RATIO D/R	AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
FIFO	1	2.97	42.2	0.17	2.6	6.98
LIFO	1	3.10	43.2	0.29	7.7	7.11
FIFO	2	3.77	47.9	0.99	12.8	7.78
LIFO	2	4.29	51.2	1.52	22.4	8.31
FIFO	3	4.94	54.5	2.19	21.2	8.95
LIFO	3	5.74	58.2	2.99	26.9	9.76
FIFO	4	6.57	61.3	3.85	24.4	10.58
LIFO	4	7.49	64.4	4.76	29.5	11.50
FIFO	5	8.42	66.9	5.72	28.2	12.43
LIFO	5	9.42	69.3	6.72	32.1	13.43

ACTUAL FORT ORD DATA

AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
3.57	42.3	1.67	42.3	8.46

TABLE 1. SIMULATION OF A BLOOD BANK USING FORT ORD DATA

$\bar{I}_i$ is 6.788 and $\bar{R}_i$ is 4.404. The mean of a geometric distribution is equal to $^q/_p$ where $q = 1-p$. Thus our estimates are $q_1 = 0.8716$ and $q_2 = 0.8149$ for the distributions of I_i and R_i respectively. Points (0,1) and $(8,q^8)$ are plotted and the line extending through them is used to approximate the data. For the case of A+ blood, the two points for I_i are (0,1) and (8, .3331) and the two points for R_i are (0,1) and (8, .1945).

The data base may not be sufficient to adequately determine distributions of I_i and R_i for the rarer blood types, but even with our limited data, the geometric distribution assumption does not appear unreasonable.

In Table 1 the results of the simulation and how they compare with actual data are presented for A+ blood. Results for the remaining blood types can be found in the Computer Output section. General information such as blood type, values of q for both I_i and R_i and length of run is presented above the tabled results. As stated before, 156 weeks was determined to be adequate to reach steady state conditions. The results are read as follows:

Under a FIFO policy with a_i equal to 2, the average number of units that become outdated per week is equal to 3.77 and the percent oudated is equal to 47.9. This results in 0.99 units of external supply per week with the percent of time that shortages occur equal to 12.8. The average inventory level at the beginning of each week is equal to 7.78.

Actual Ft. Ord data is listed in the table and except for the percentage of time that shortages occur, the simulation results compare favorably with this actual data. The purpose of the simulation model is to indicate general trends of $E[O_i]$ and $E[S_i]$ when either critical parameters such as $E[R_i]$, $E[I_i]$, a_i, or the inventory policies are varied. With this purpose in mind, the results of the simulation agree sufficiently well with actual data, thus verifying the simulation model.

VIII. ANALYSIS OF VARIOUS OPERATING POLICIES

In this section we discuss the results found when blood bank operations are simulated under a variety of policies. Since we already have determined I_i and R_i are distributed geometrically, this distribution is used in all simulations discussed. As a specific example, the data from Ft. Ord for A+ blood is used. Two approaches are employed for both FIFO and LIFO policies with a_i taking on values of 1 through 5. The first approach holds the expected value of I_i constant while the expected value of R_i varies. The second approach holds the expected value of R_i constant while the expected value of I_i varies. The results of the simulation are plotted in Figures 4 to 9. The outcomes for all FIFO policies are displayed. For $a_i = 2$, the result of the LIFO policy is also plotted to indicate upper and lower bounds for $E[O_i]$ and $E[S_i]$. Additional results of LIFO policies were not plotted so as to keep the graphs from becoming too cluttered.

Figure 4 depicts what happens to $E[O_i]$ for various values of a_i when $E[I_i]$ is held constant and $E[R_i]$ is allowed to vary. For any given ratio of $E[R_i]/E[I_i]$, $E[O_i]$ can be significantly reduced by reducing the safety factor a_i. For values of a_i above 3, reduction in outdating can be achieved by reducing $E[R_i]$ until a ratio of 0.2 or below is reached. For values of a_i below 2, reducing $E[R_i]$ may lead to an increase in $E[O_i]$. With a relatively low safety factor, reducing $E[R_i]$ while $E[I_i]$ remains constant will tend to increase outdating because internal inputs exceed both usage and demand requirements. For larger values of a_i, the demand requirements drive inventory levels up, thus a reduction in $E[R_i]$ results in reduced demand, lower inventory levels and less outdating.

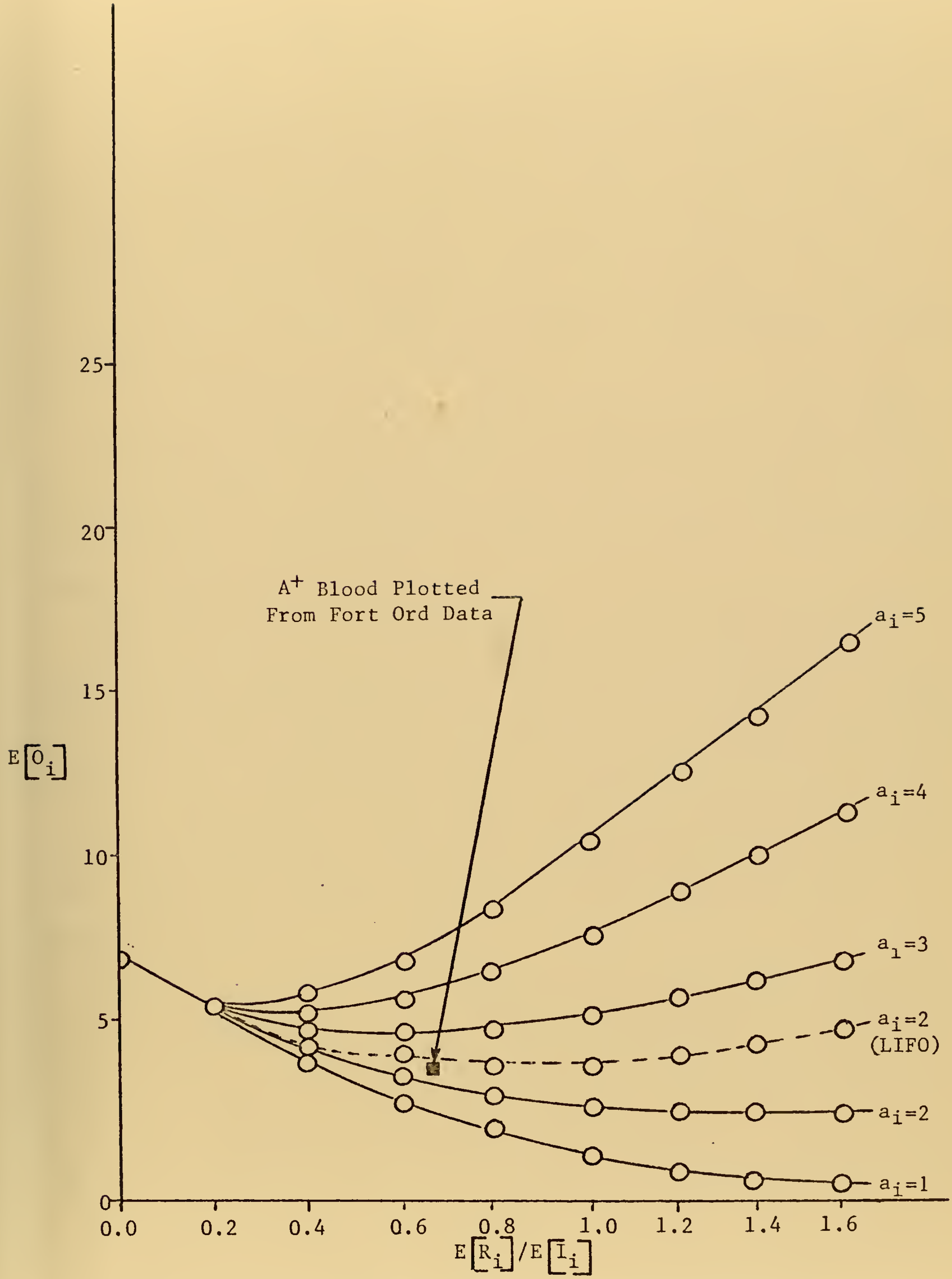


Fig. 4 Outdated A+ Blood, $E[R_i]$ Varies, $E[I_i]$ Constant

The dark square represents the value for A+ blood obtained from Ft. Ord data. The ratio of $E[R_i]/E[I_i]$ equals 0.649 and the value of $E[O_i]$ equals 3.57 units per week. The dotted line represents a LIFO policy with $a_i=2$. Therefore, for A+ blood, Ft. Ord appears to be operating between a FIFO and LIFO policy with a safety factor of 2. Without changing $E[R_i]$, outdating can be reduced by moving closer to a FIFO policy or by decreasing the safety factor. If only that amount of A+ blood that will be transfused is demanded ($a_i=1$), then outdating can be reduced to approximately 2.6 units per week.

A decrease in outdating could also be obtained by increasing $E[R_i]$. One way this might be accomplished is by supplying additional A+ blood to other hospitals, but before this is done, other aspects of this alternative should be considered.

Figure 5 shows what happens to $E[S_i]$ for various values of a_i when plotted against $E[R_i]/E[I_i]$. As in the first graph, the value of $E[I_i]$ is held constant while $E[R_i]$ varies. Again, for a given value of $E[R_i]/E[I_i]$, shortages can be reduced by reducing a_i. Shortages can also be reduced by reducing $E[R_i]$ for all values of a_i greater than one. Reducing $E[R_i]$ while $E[I_i]$ remains constant results in additional inventories, thus reducing shortages.

Using data obtained from Ft. Ord for A+ blood, the value of $E[S_i]$ is found to be 1.67 units per week. As before, $E[R_i]/E[I_i] = 0.649$ and the point that indicates these results is represented by the dark square. The dotted line represents a LIFO policy with a_i equal to 2. Without changing $E[R_i]$, shortages can be reduced by following a FIFO inventory policy and/or by reducing a_i. If $a_i = 1$, then $E[S_i]$ would average 0.4 units per week. It is also noted that any increase in $E[R_i]$ will tend to increase shortages.

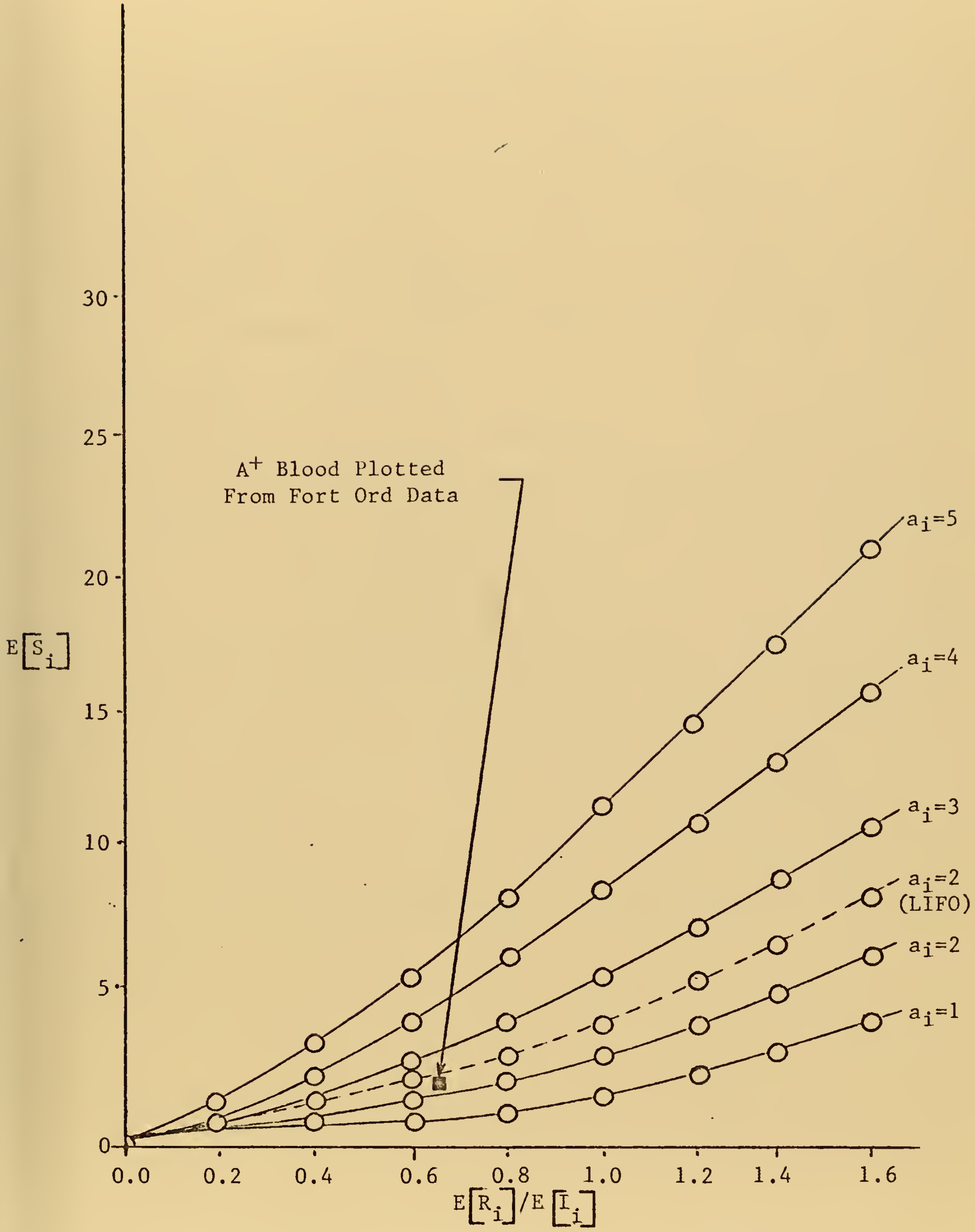


Fig. 5 Shortages of A+ Blood, $E[R_i]$ Varies, $E[I_i]$ Constant

As stated before, the problems of outdating and shortages must be looked at together because a reduction in one may tend to increase the other. Figure 6 is a combination of Figures 4 and 5. The effects of both outdating and shortages are displayed for various values of a_i. The dashed lines indicate constant values of $E[R_i]/E[I_i]$ which are increasing from left to right. Reducing a_i while holding $E[R_i]/E[I_i]$ constant, reduces both $E[O_i]$ and $E[S_i]$ by moving down and parallel to the dashed lines representing constant $E[R_i]/E[I_i]$ values. A change in $E[R_i]$ will affect outdating and shortages in different ways depending upon initial values of $E[O_i]$ and $E[S_i]$. To illustrate this point, the values of $E[S_i]$ and $E[O_i]$ for A+ blood from Ft. Ord data are plotted. As before, if a FIFO inventory policy is followed, both $E[O_i]$ and $E[S_i]$ can be reduced. Both $E[O_i]$ and $E[S_i]$ can also be reduced if the safety factor is decreased. For $a_i = 1$, with the ratio of $E[R_i]/E[I_i]$ remaining constant at 0.649, $E[O_i]$ drops to 2.6 units per week and $E[S_i]$ drops to about 0.4 units per week. If a_i and the present inventory policy remain unchanged, an increase in $E[R_i]$ will tend to increase shortages more than it will decrease outdating. A decrease in $E[R_i]$ will cause outdating to increase approximately as much as shortages decrease until a ratio of 0.6 is reached. Once $E[R_i]/E[I_i]$ becomes less than 0.6, decreasing $E[R_i]$ will cause outdating to increase <u>more</u> than shortages decrease.

Realizing that it is not always possible for a blood bank to affect the amount of blood being transfused, another alternative will be examined. We feel that certain blood banks can influence the number of donors they receive. Therefore, the same type of analysis will be done by holding $E[R_i]$ constant and varying $E[I_i]$.

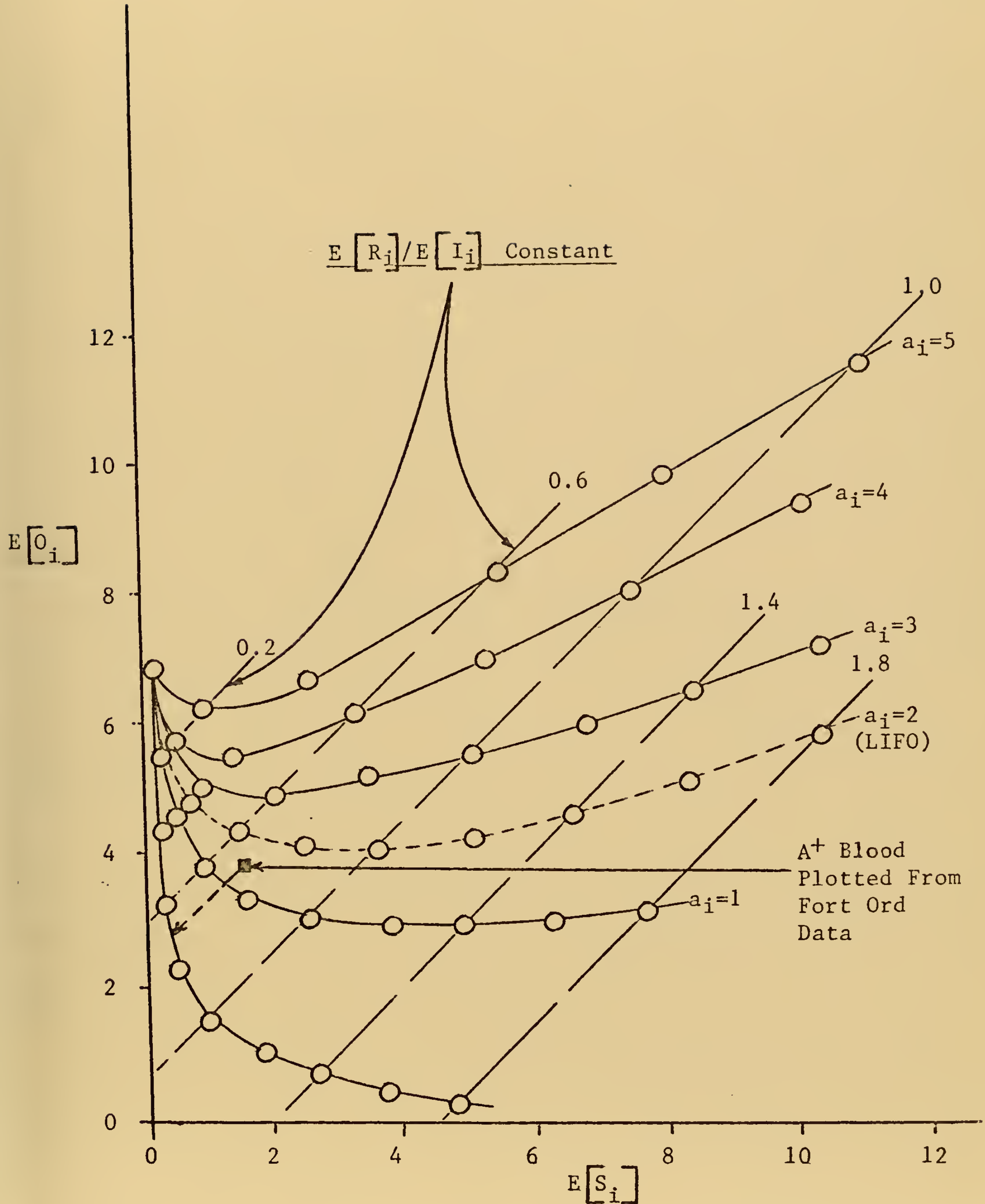


Fig. 6 Outdating vs Shortages, $E[R_i]$ Varies, $E[I_i]$ Constant.

Figure 7 indicates what happens to $E[O_i]$ for various values of a_i when plotted against the ratio $E[R_i]/E[I_i]$. The expected value of R_i is held constant while the expected value of I_i is varied. Any reduction in a_i reduces $E[O_i]$ for all values of $E[R_i]/E[I_i]$. Decreasing $E[I_i]$ also reduces outdating. Since more blood is collected than is actually transfused, common values of $E[R_i]/E[I_i]$ will tend to be less than one. In this range of $E[R_i]/E[I_i]$ an increase in $E[I_i]$ will significantly increase outdating (especially for those values of $E[R_i]/E[I_i]$ that are less than 0.6). The point for A+ blood is plotted using $E[O_i] = 3.57$ and $E[R_i]/E[I_i] = .649$. As previously shown, the result falls between FIFO and LIFO policies with $a_i = 2$. If the safety factor were reduced to one and a strict FIFO policy were followed, an average of 2.6 units of A+ blood would become outdated per week. If fewer donors were processed, $E[O_i]$ would again decrease, but how would this affect $E[S_i]$?

When shortages are plotted against $E[R_i]/E[I_i]$ as in Figure 8, we see that reducing $E[I_i]$ increases $E[S_i]$. As before, any reduction in a_i will tend to reduce $E[S_i]$. In the example for A+ blood, $E[S_i] = 1.67$ and $E[R_i]/E[I_i] = 0.649$. This point lies between FIFO and LIFO policies for $a_i = 2$. If $E[I_i]$ is held constant and a_i is reduced to one, average shortages will be reduced to approximately 0.4 units per week. If $a_i = 2$ and $E[I_i]$ is reduced until the ratio of $E[R_i]/E[I_i] = 1.2$, average shortages will increase to about 2.7 units per week.

Both $E[O_i]$ and $E[S_i]$ must be considered before any decision is made to increase or decrease $E[I_i]$. Figure 9 combines Figures 7 and 8. The effects of changing $E[I_i]$ on both outdating and shortages are shown for values of a_i from 1 through 5. The dashed lines represent constant values of $E[R_i]/E[I_i]$ which are increasing from left to right. Decreasing a_i

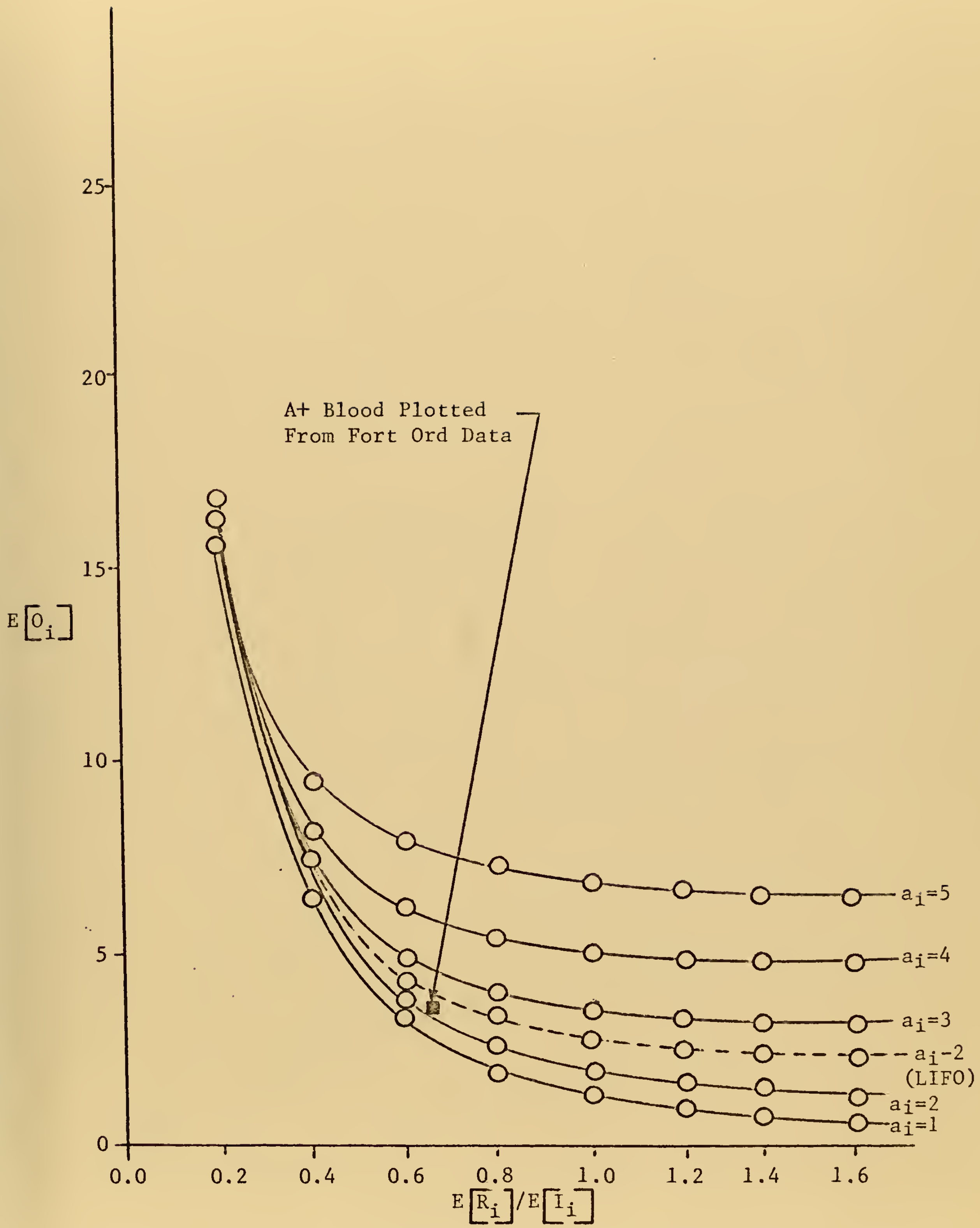


Fig. 7 Outdated A+ Blood, $E[R_i]$ Constant, $E[I_i]$ Varies

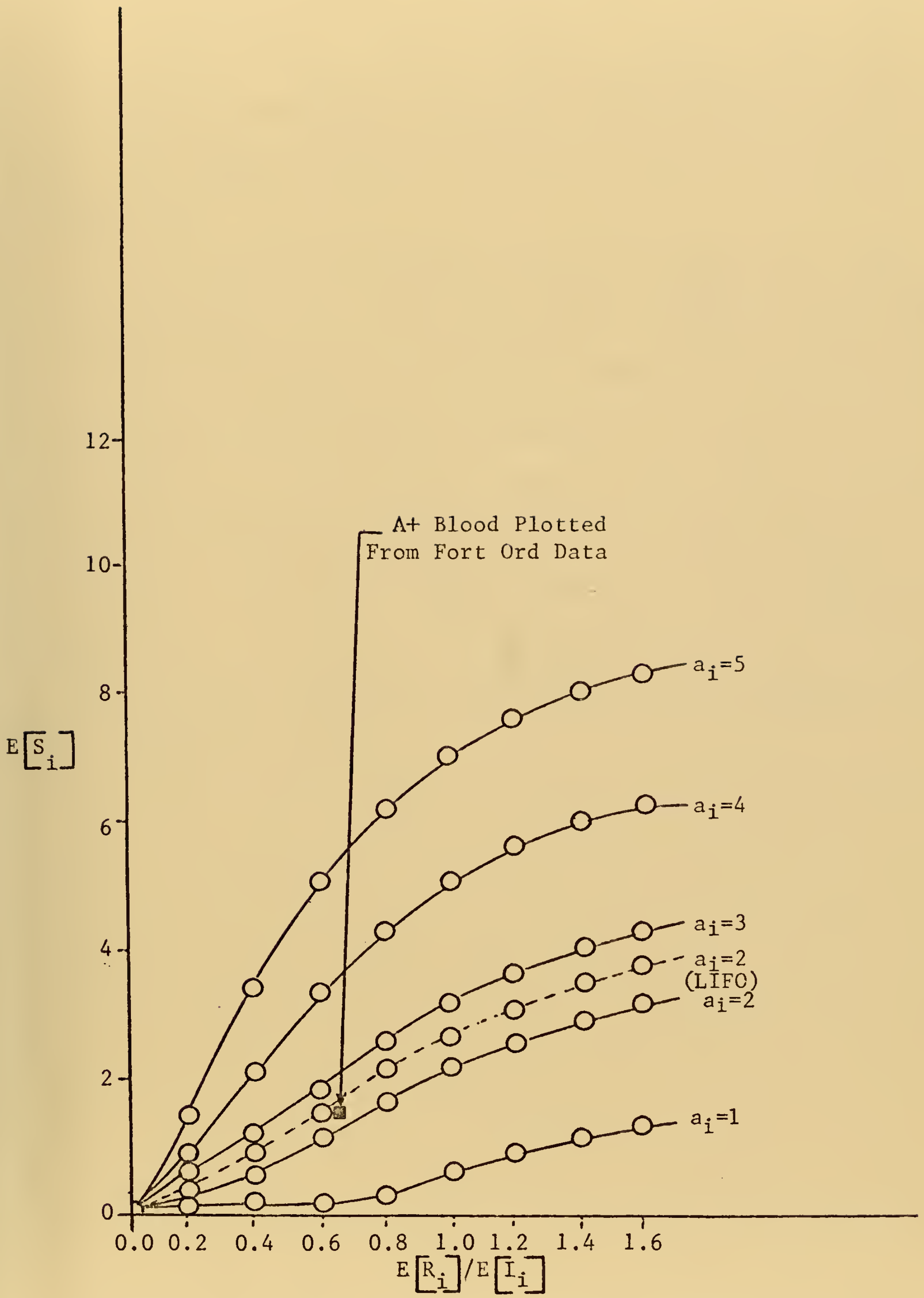


Fig. 8 Shortages of A+ Blood, $E[R_i]$ Constant, $E[I_i]$ Varies.

while holding $E[I_i]$ constant will reduce both outdating and shortages by moving down and parallel to the dashed lines. For values of $E[R_i]/E[I_i]$ that are less than 1.0, reducing $E[I_i]$ will greatly reduce $E[O_i]$ with only minor increases in $E[S_i]$. For values of $E[R_i]/E[I_i]$ greater than 1.0, decreasing $E[I_i]$ will tend to increase shortages more and decrease outdating less.

Data results for A+ are again plotted for $E[O_i] = 3.57$, $E[S_i] = 1.67$ and $E[R_i]/E[I_i] = 0.649$. From this point, if $E[I_i]$ is held constant and a FIFO policy with $a_i = 1$ is followed, average outdating would drop to 2.6 units per week and average shortages would be reduced to 0.4 units per week. If a_i and the present inventory policy remain unchanged, an increase in $E[I_i]$ would slightly decrease shortages, but greatly increase outdating. A reduction in $E[I_i]$ would tend to decrease $E[O_i]$ and increase $E[S_i]$ by the same amount until $E[R_i]/E[I_i]$ reaches a value of approximately 1.0. Additional reduction of $E[I_i]$ would then cause $E[S_i]$ to increase more than $E[O_i]$ would decrease.

We have shown how changes in blood banking policies can affect outdating and shortages by using one blood type as an example. Each of the eight blood types would have to be examined in the same manner before decisions concerning $E[I_i]$ and $E[R_i]$ could be made. We have also shown that any reduction in the safety factor will also reduce both outdating and shortages. The ideal value of a_i would be 1.0, but this is not feasible because of the risk involved. A reduction in a_i <u>is</u> possible in cases where it is unnecessarily high. LIFO and FIFO inventory policies indicate upper and lower bounds on $E[S_i]$ and $E[O_i]$ with a strict FIFO policy giving the lowest values for these quantities for feasible values of a_i. A blood bank such as Ft. Ord might find it easier to change $E[I_i]$ rather than $E[R_i]$,

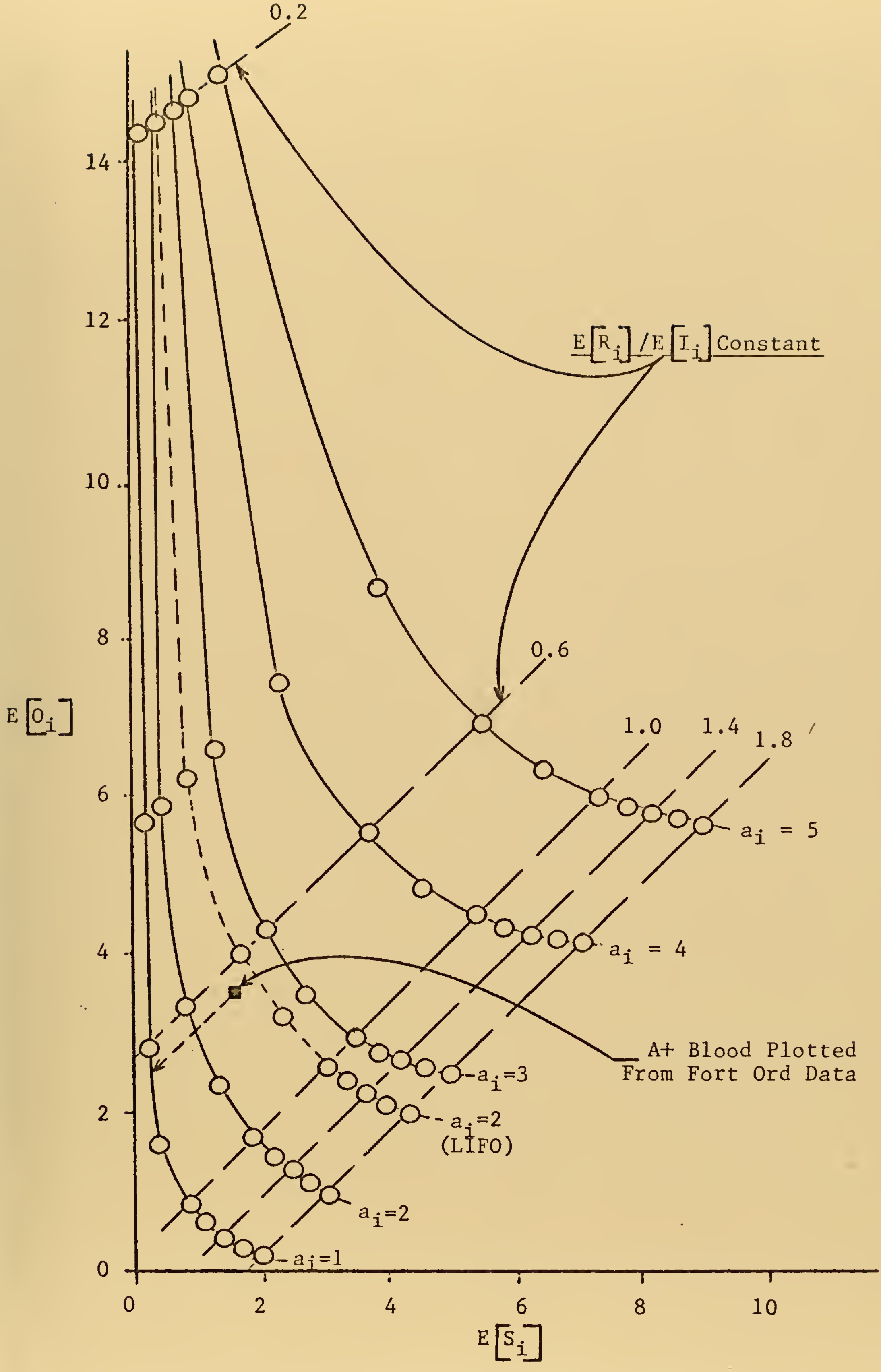


Fig. 9 Outdating vs Shortages, $E[R_i]$ Constant, $E[I_i]$ Varies.

while the Red Cross Center at San Jose might find it easier to change $E[R_i]$ by servicing additional hospitals rather than changing $E[I_i]$.

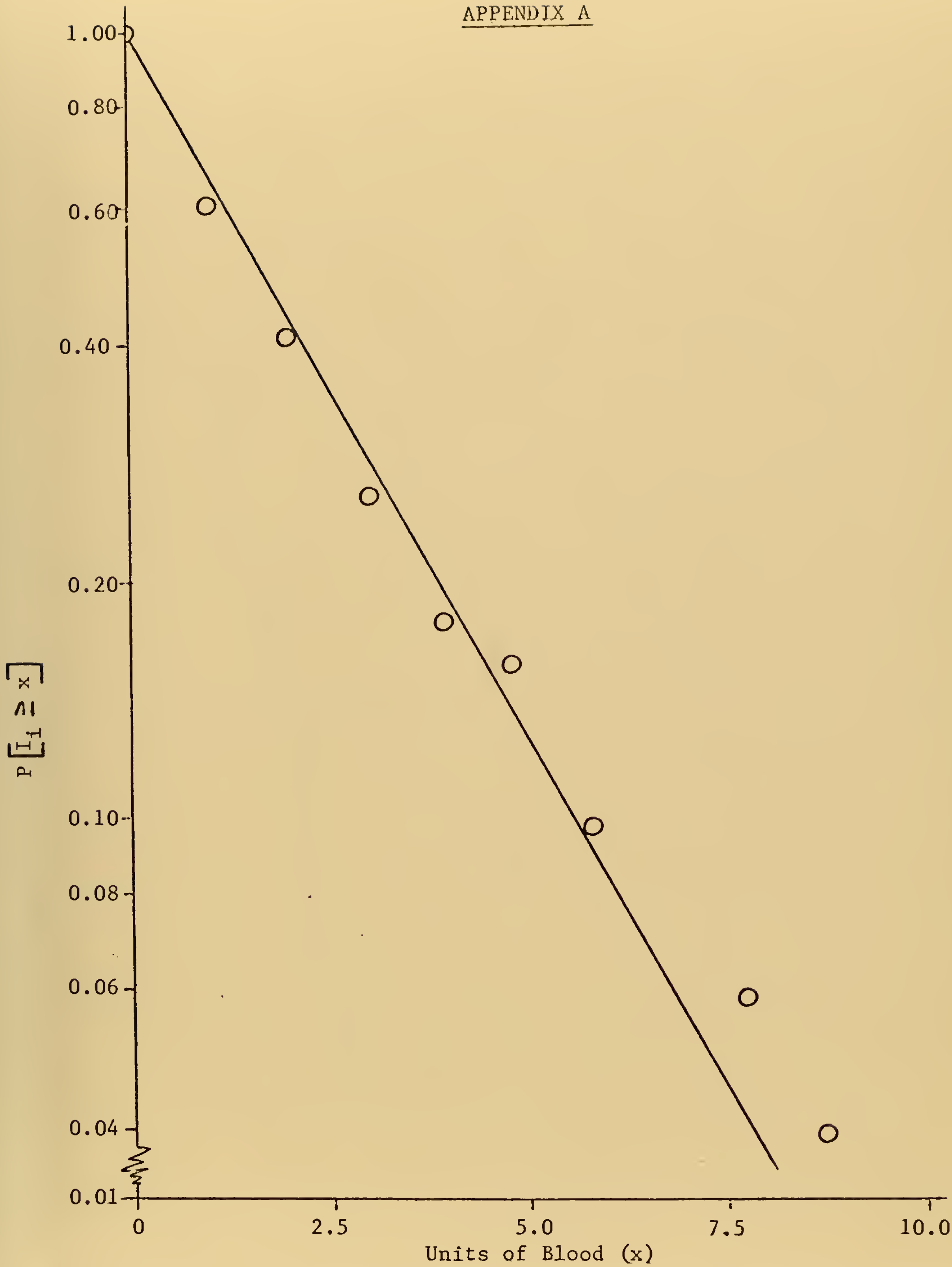


Fig. 10 Distribution of A⁻ Blood Internally Supplied at Fort Ord, FY71.

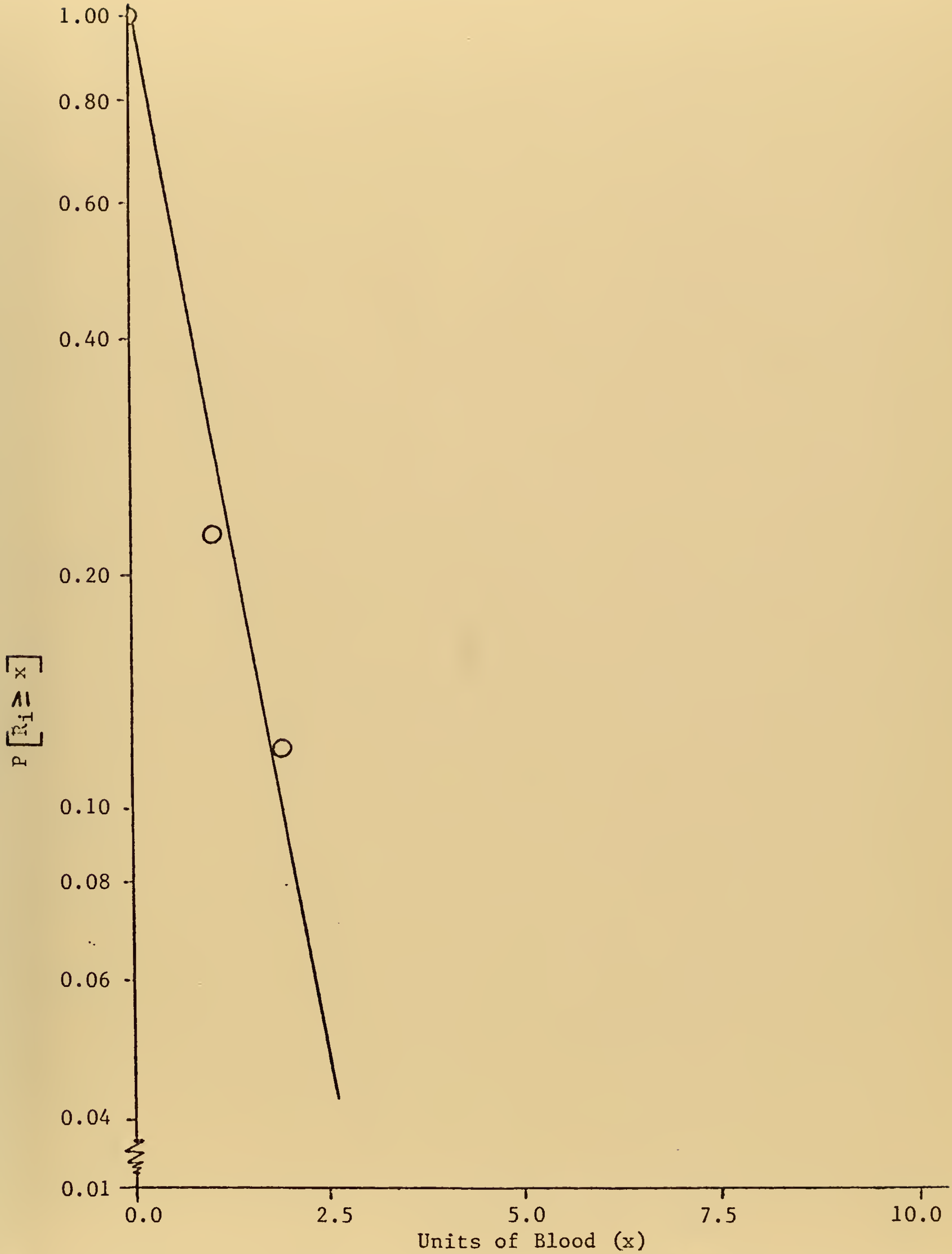


Fig. 11 Distribution of A^- Blood Transfused at Fort Ord, FY71.

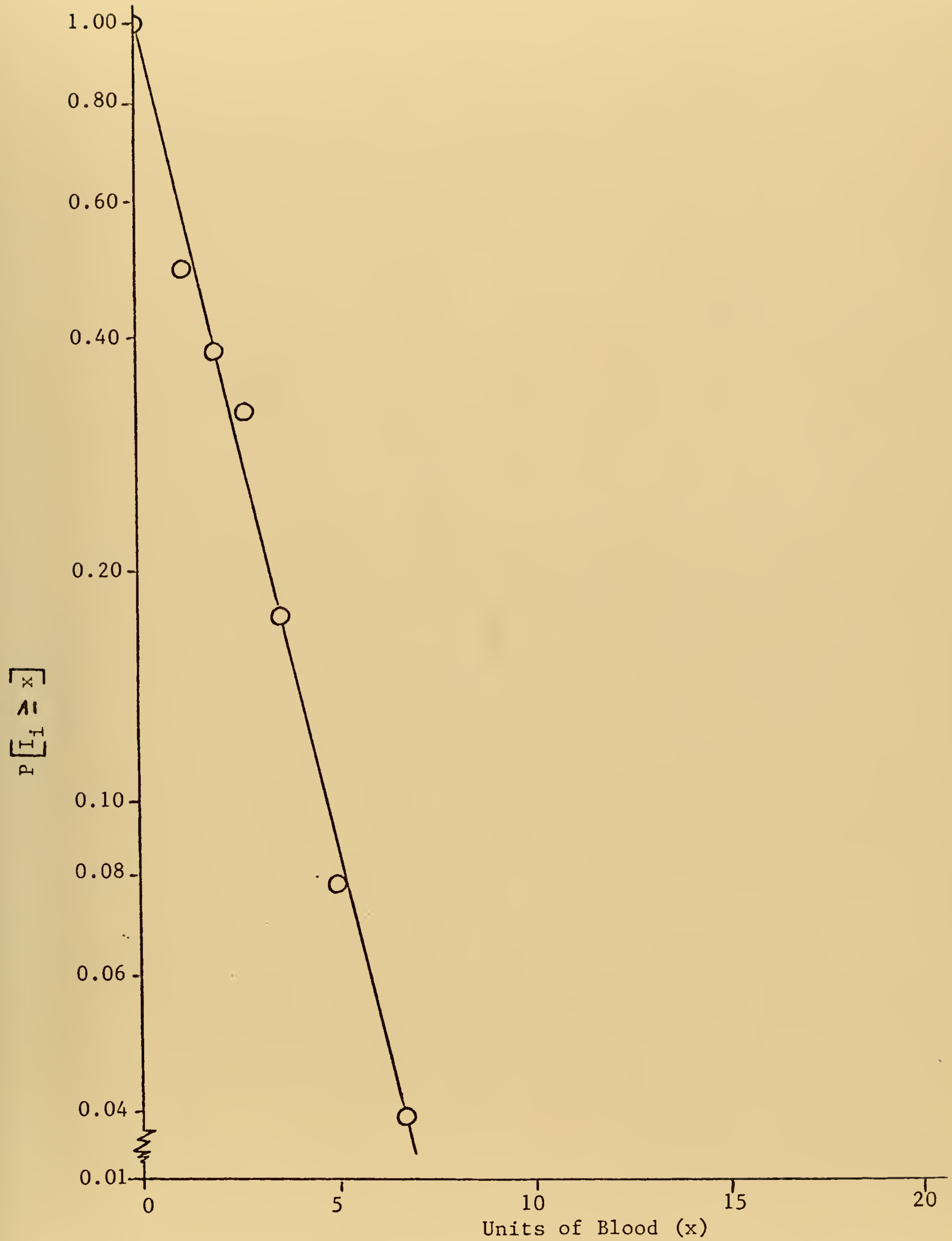


Fig. 12 Distribution of B^+ Blood Internally Supplied at Fort Ord, FY71.

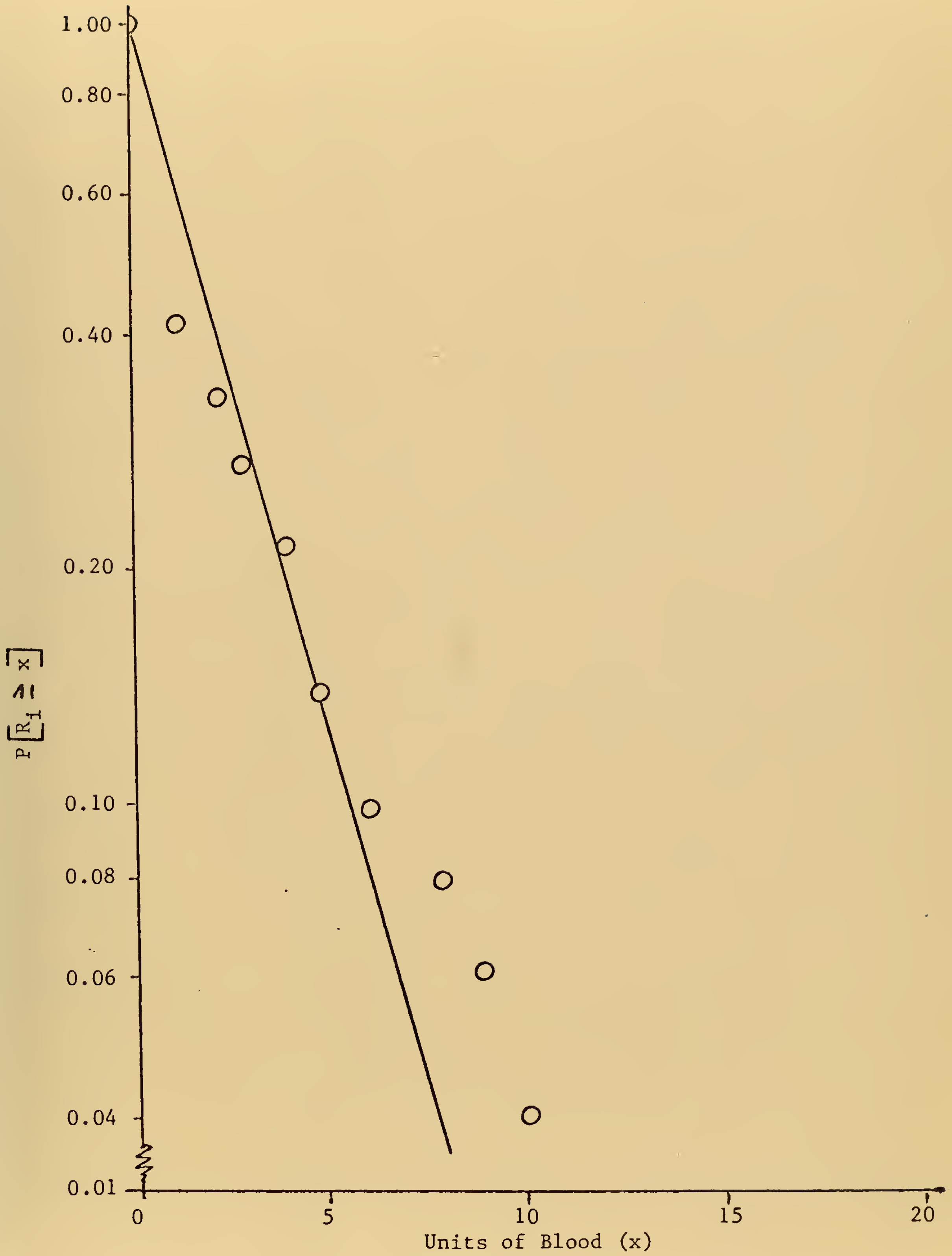


Fig. 13 Distribution of B^+ Blood Transfused at Fort Ord, FY71.

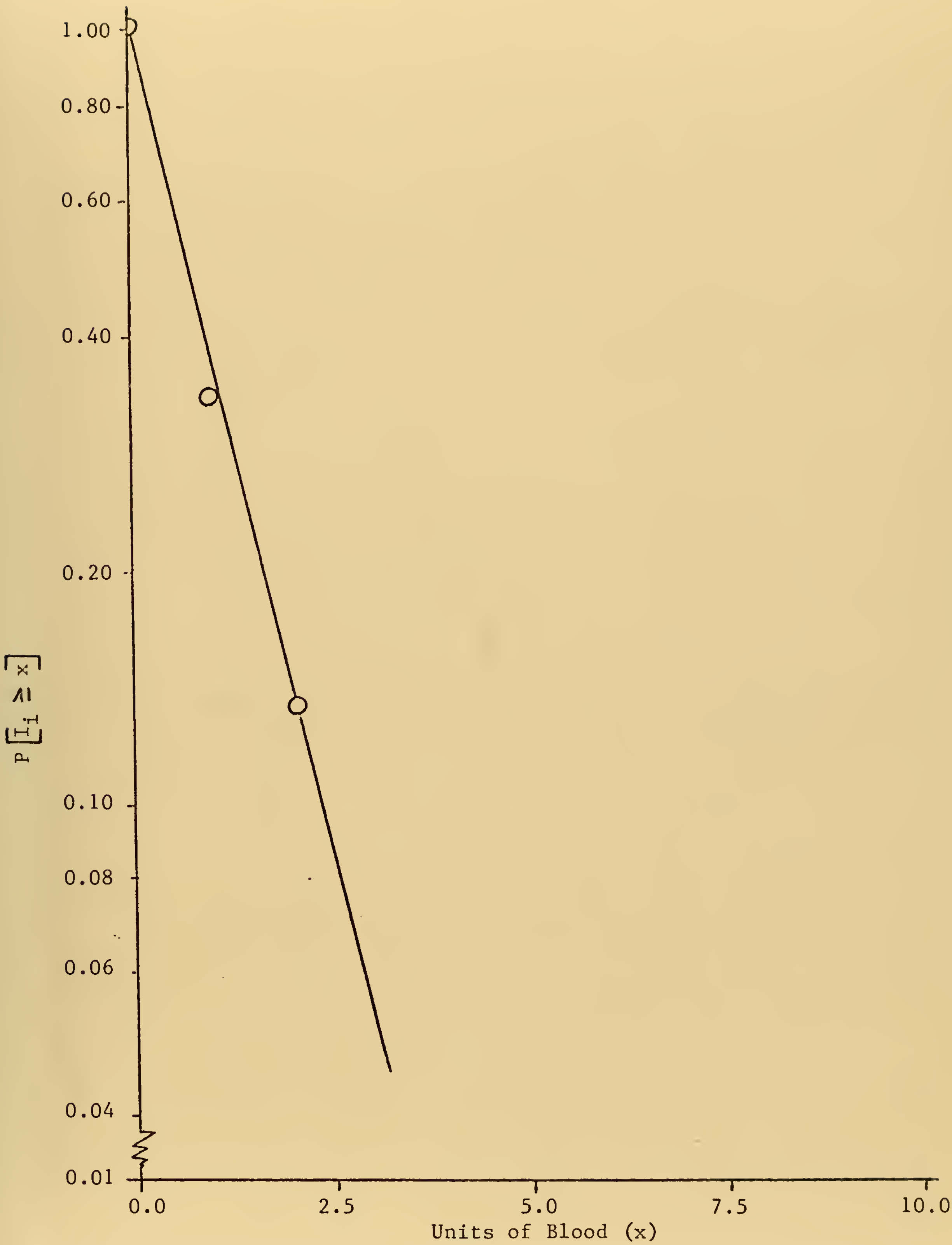


Fig. 14 Distribution of B^- Blood Internally Supplied at Fort Ord, FY71.

Fig. 15 Distribution of B^- Blood Transfused at Fort Ord, FY71.

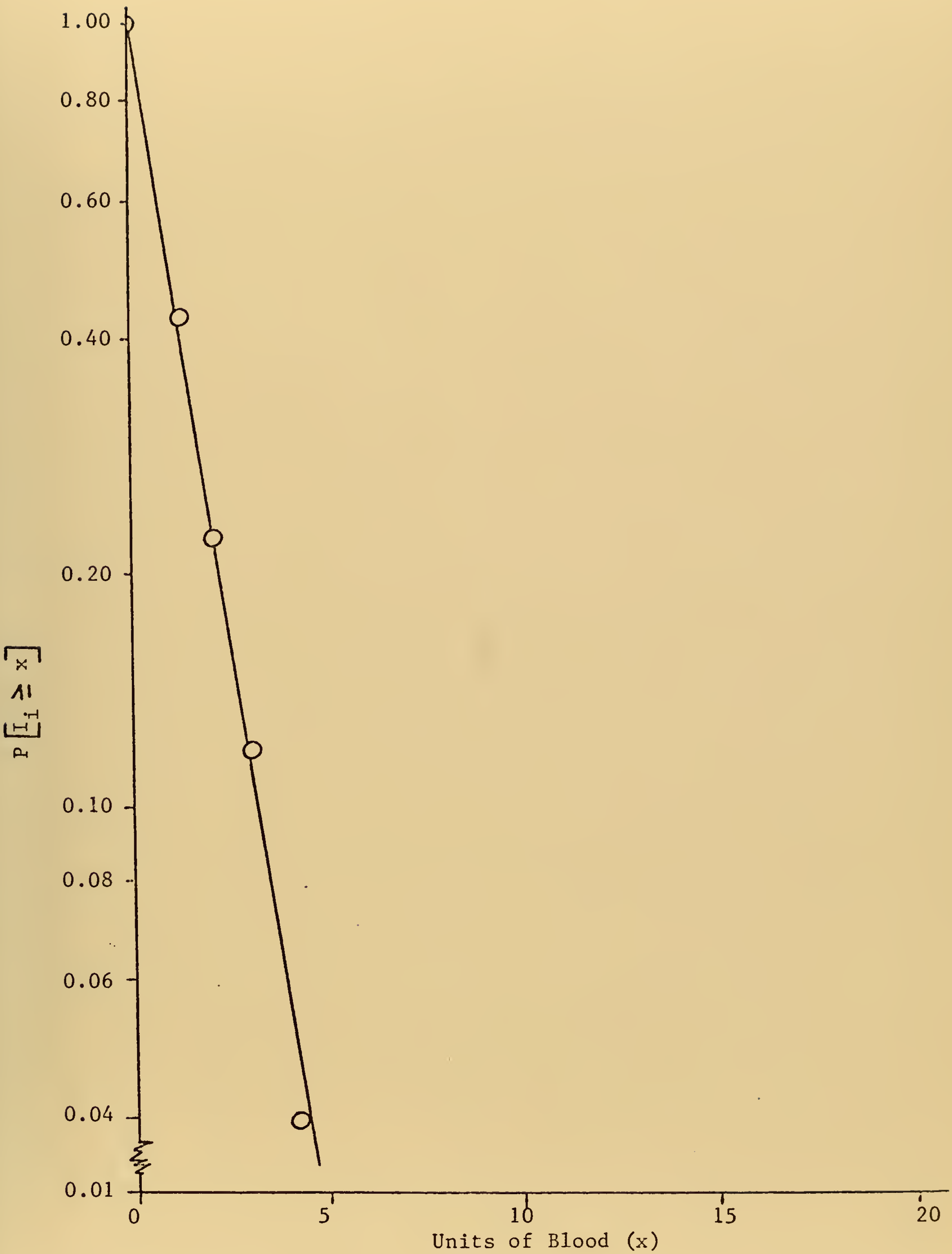


Fig. 16 Distribution of AB^+ Blood Internally Supplied at Fort Ord, FY71

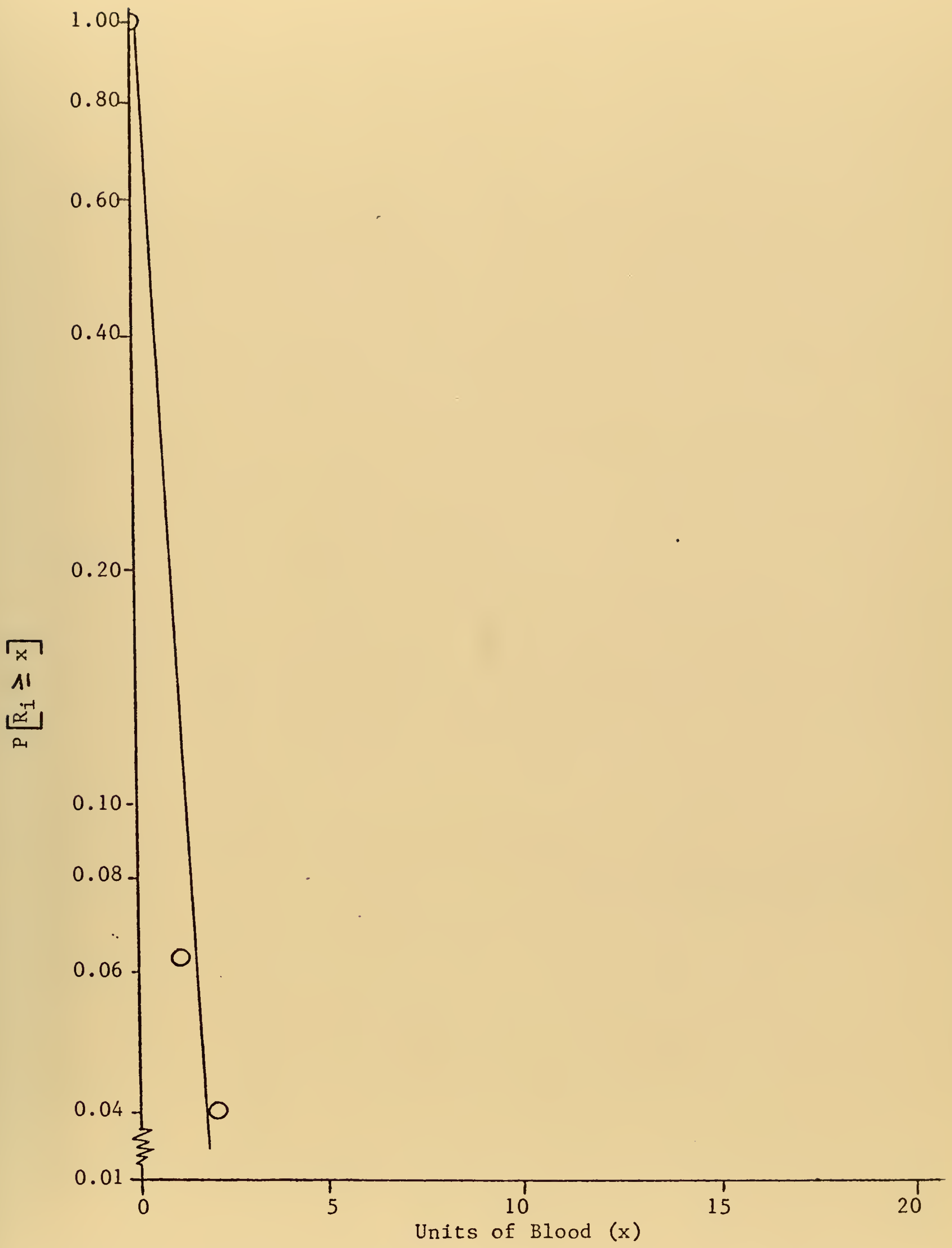


Fig. 17 Distribution of AB^+ Blood Transfused at Fort Ord, FY71.

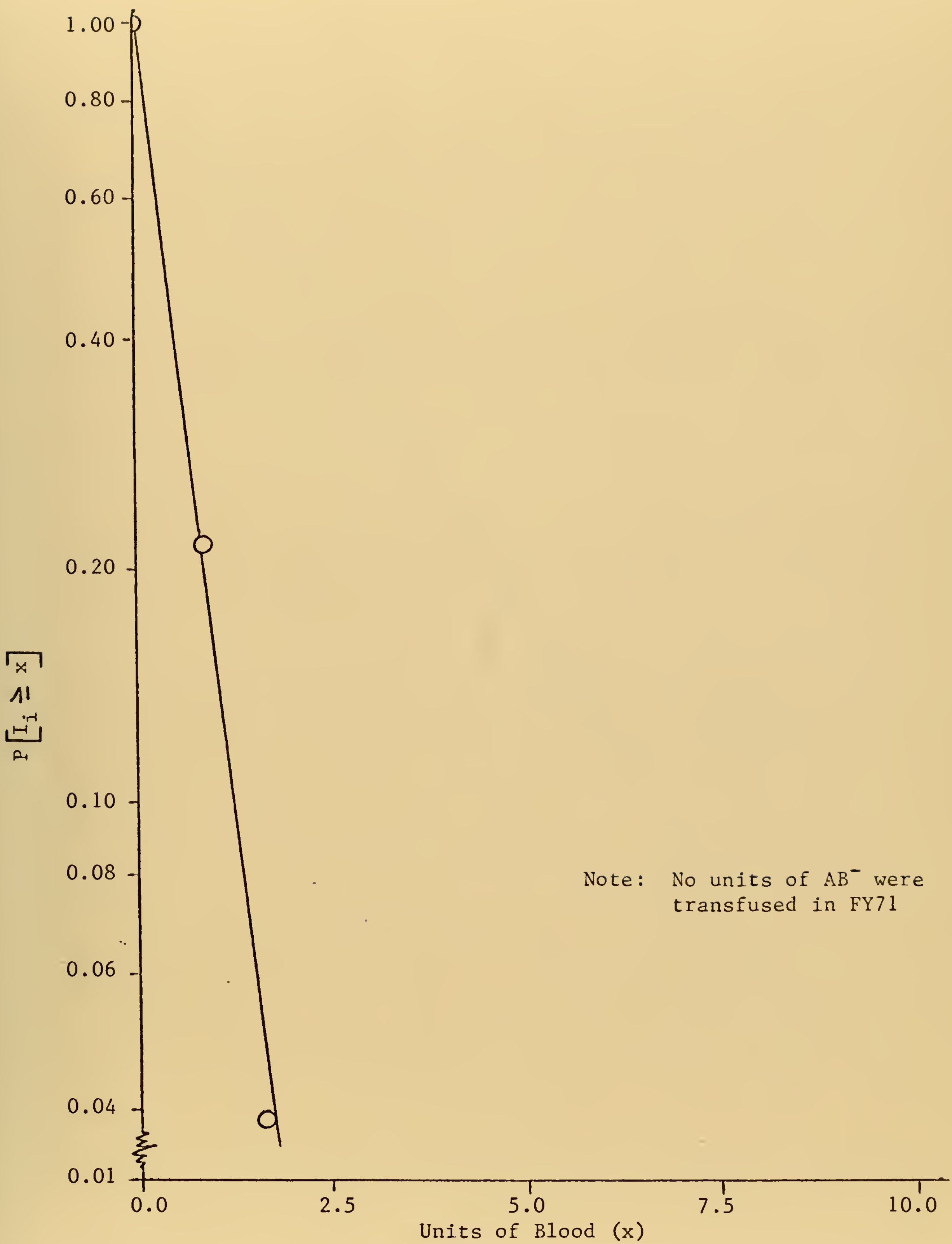


Fig. 18 Distribution of AB^- Blood Internally Supplied at Fort Ord, FY71.

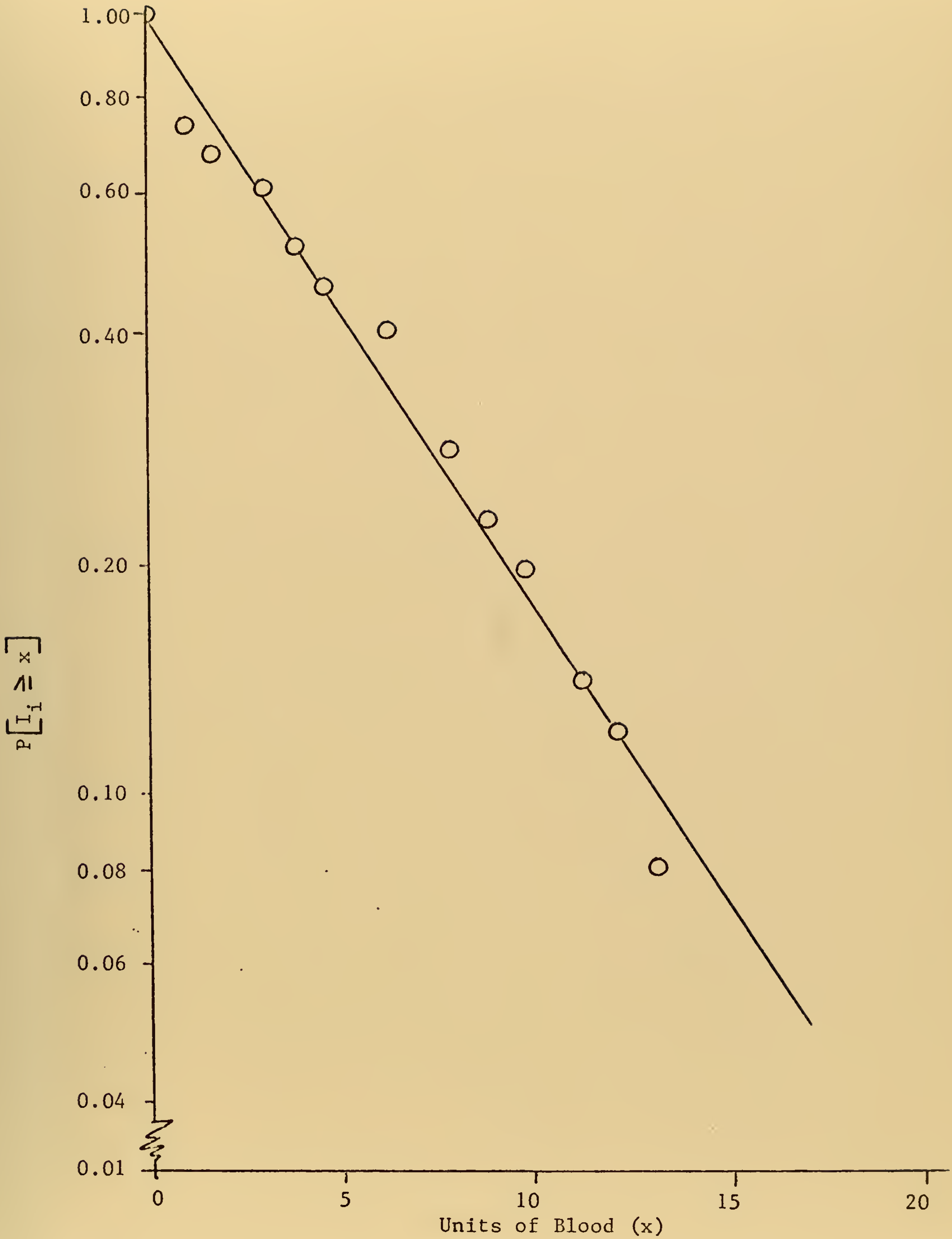


Fig. 19 Distribution of 0^+ Blood Internally Supplied at Fort Ord, FY71.

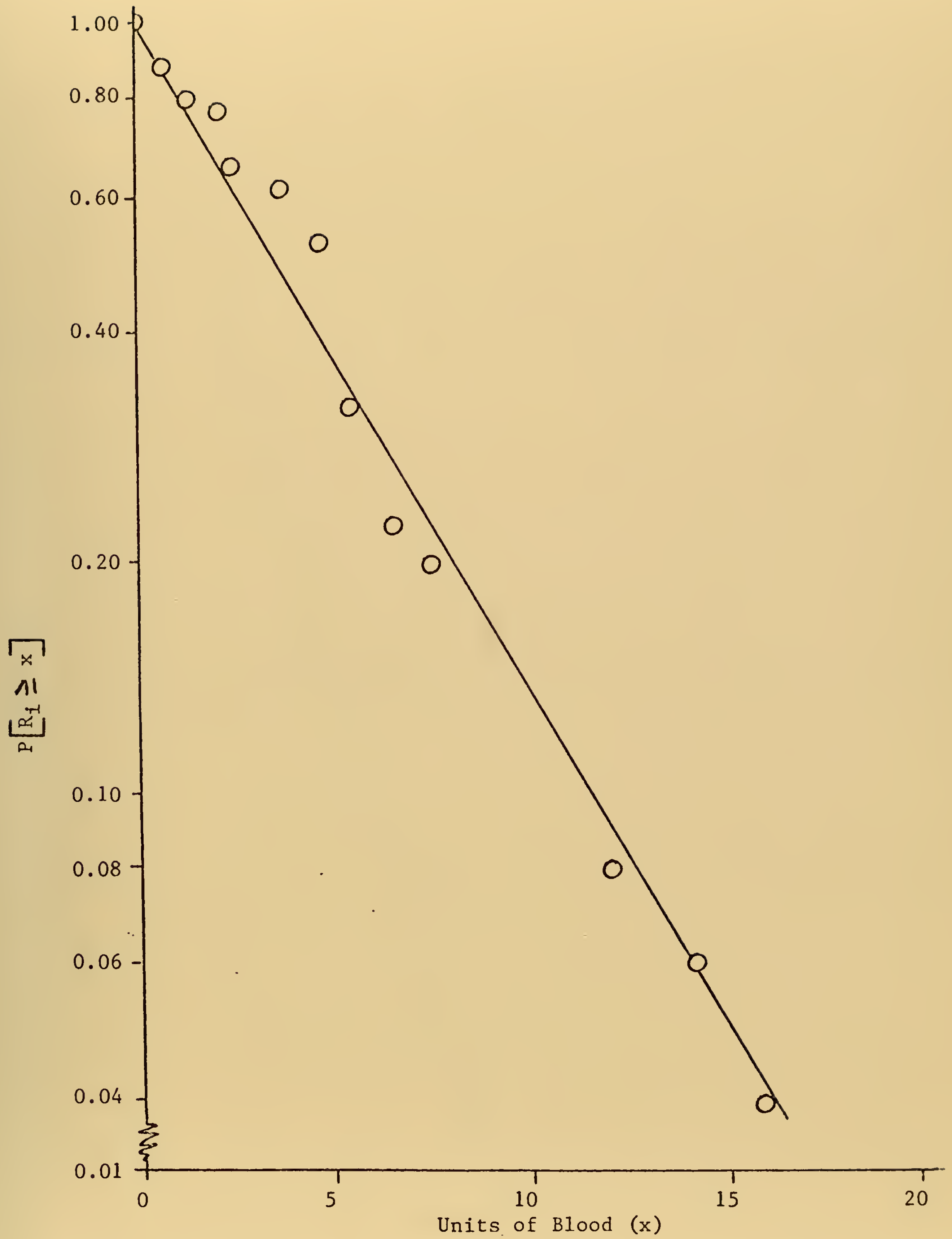


Fig. 20 Distribution of O^+ Blood Transfused at Fort Ord, FY71.

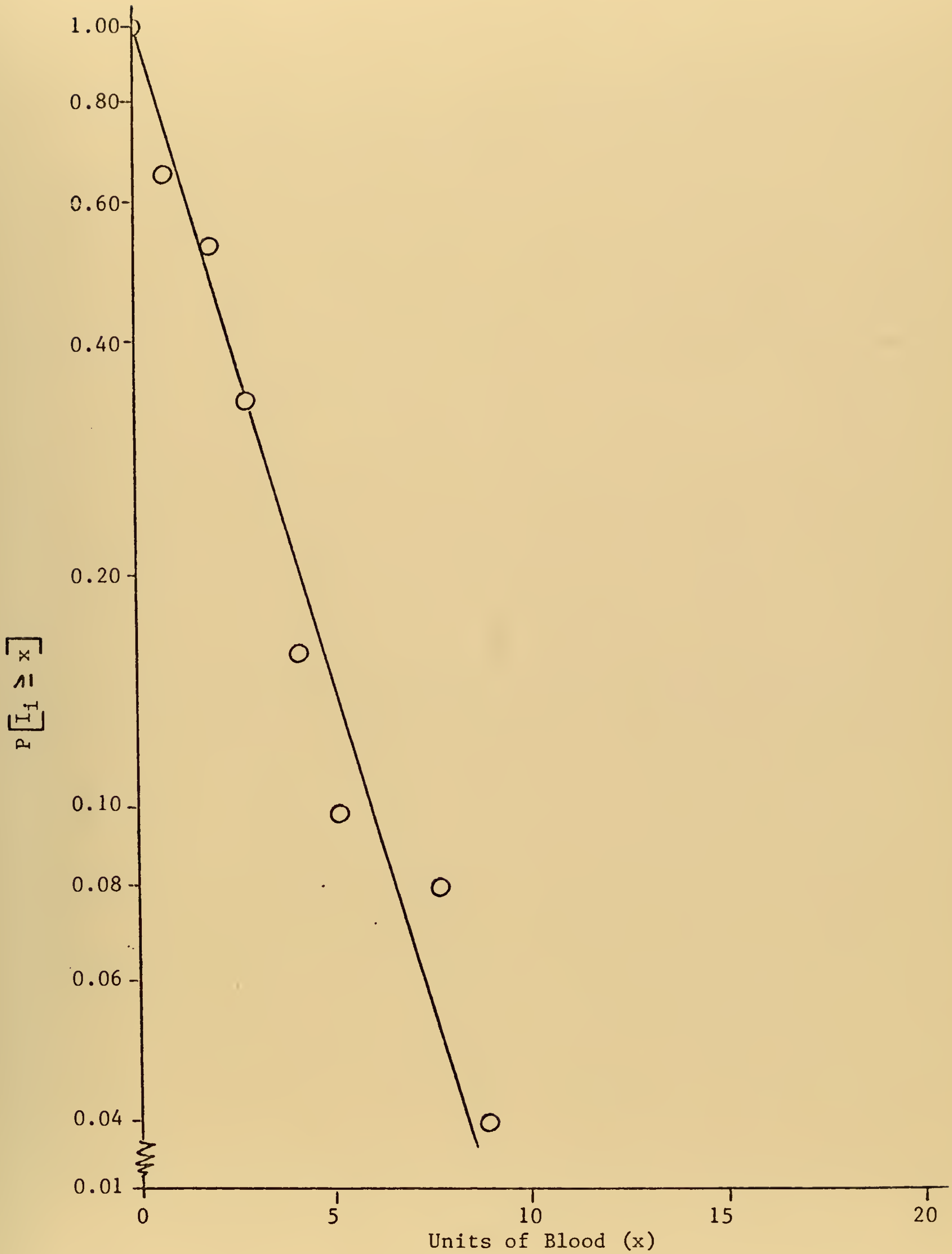


Fig. 21 Distribution of O^- Blood Internally Supplied at Fort Ord, FY71.

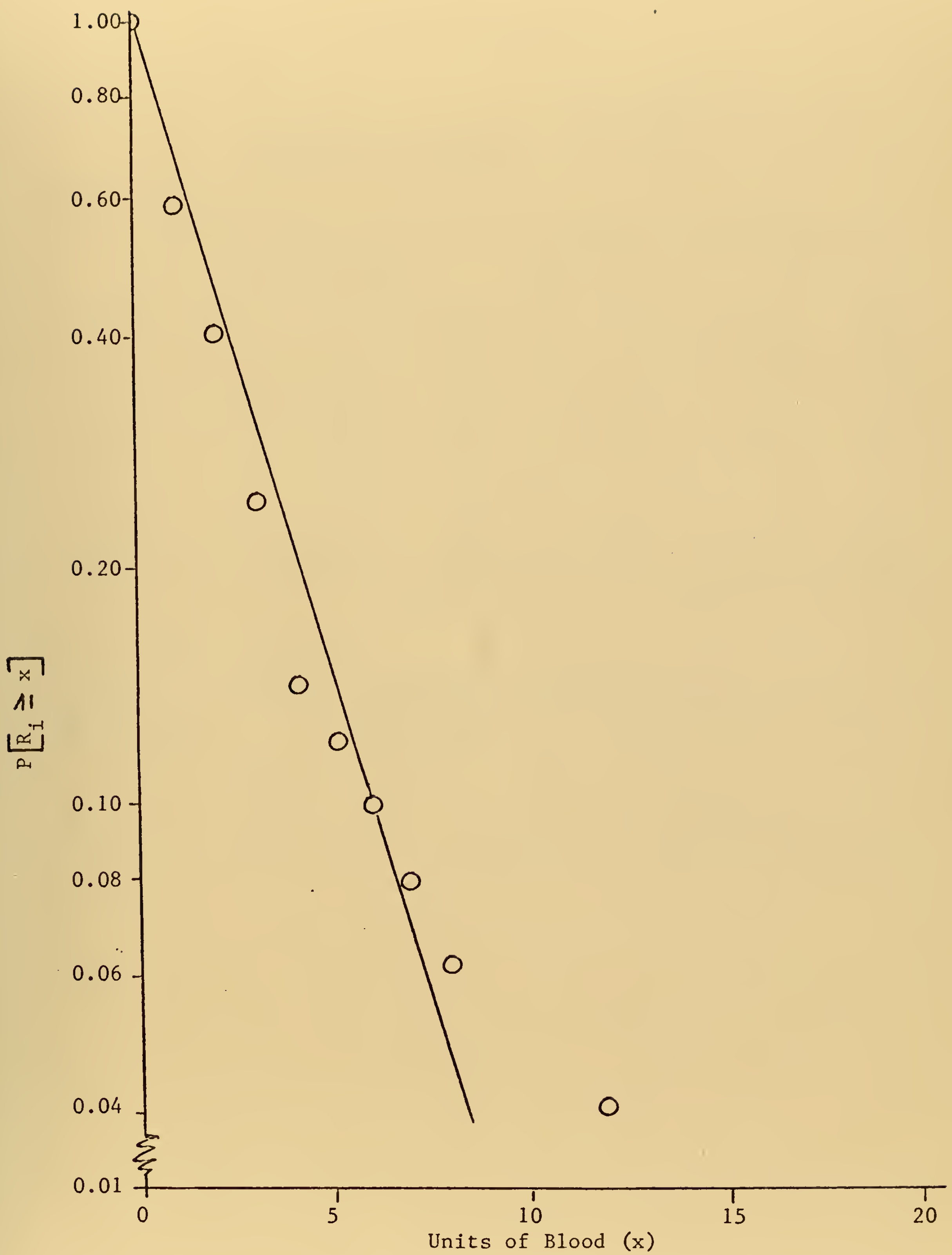


Fig. 22 Distribution of O^- Blood Transfused at Fort Ord, FY71.

COMPUTER OUTPUT

BLOOD TYPE   INPUT DATA   TIME PERIOD

A-   Q INTERNAL =.646259   156 WEEKS
Q REQUIRED =.306667

SIMULATION RESULTS

POLICY	RATIO D/R	AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
FIFO	1	1.47	79.0	0.03	1.3	1.84
LIFO	1	1.47	79.0	0.03	1.3	1.85
FIFO	2	1.51	79.5	0.07	2.6	1.88
LIFO	2	1.53	79.6	0.08	3.2	1.90
FIFO	3	1.61	80.4	0.17	5.8	1.98
LIFO	3	1.63	80.6	0.19	6.4	2.00
FIFO	4	1.74	81.6	0.29	9.0	2.11
LIFO	4	1.76	81.8	0.31	9.0	2.13
FIFO	5	1.88	82.8	0.44	9.6	2.25
LIFO	5	1.92	83.1	0.47	11.5	2.29

ACTUAL FORT ORD DATA

AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
1.35	69.3	0.12	9.6	1.94

TABLE 2. SIMULATION OF A BLOOD BANK USING FORT ORD DATA

BLOOD TYPE INPUT DATA TIME PERIOD

B+ Q INTERNAL =.600000 156 WEEKS
Q REQUIRED =.631206

SIMULATION RESULTS

POLICY	RATIO D/R	AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
FIFO	1	0.42	21.2	0.44	21.2	1.95
LIFO	1	0.50	24.5	0.52	24.4	2.03
FIFO	2	0.90	36.6	0.92	23.1	2.43
LIFO	2	1.15	42.5	1.17	28.8	2.68
FIFO	3	1.63	51.1	1.66	25.6	3.16
LIFO	3	1.90	55.0	1.94	30.1	3.44
FIFO	4	2.44	60.9	2.47	28.8	3.97
LIFO	4	2.74	63.7	2.78	32.7	4.28
FIFO	5	3.26	67.5	3.31	30.8	4.79
LIFO	5	3.60	69.6	3.65	34.6	5.13

ACTUAL FORT ORD DATA

AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
0.67	27.3	0.96	32.7	2.46

TABLE 3. SIMULATION OF A BLOOD BANK USING FORT ORD DATA

BLOOD TYPE   INPUT DATA   TIME PERIOD

B-   Q INTERNAL =.395349   156 WEEKS
Q REQUIRED =.223881

SIMULATION RESULTS

POLICY	RATIO D/R	AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
FIFO	1	0.43	63.2	0.03	2.6	0.67
LIFO	1	0.44	63.6	0.04	3.2	0.68
FIFO	2	0.51	67.2	0.12	7.7	0.76
LIFO	2	0.53	67.8	0.13	8.3	0.77
FIFO	3	0.63	71.5	0.23	11.5	0.87
LIFO	3	0.65	72.3	0.26	13.5	0.90
FIFO	4	0.79	75.9	0.39	14.7	1.03
LIFO	4	0.82	76.6	0.42	17.3	1.06
FIFO	5	0.96	79.4	0.56	16.0	1.21
LIFO	5	0.99	79.9	0.60	17.9	1.24

ACTUAL FORT ORD DATA

AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
0.46	61.5	0.10	7.7	0.75

TABLE 4. SIMULATION OF A BLOOD BANK USING FORT ORD DATA

BLOOD TYPE   INPUT DATA   TIME PERIOD

AB+   Q INTERNAL =.458333   156 WEEKS
Q REQUIRED =.161290

SIMULATION RESULTS

POLICY	RATIO D/R	AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
FIFO	1	0.69	79.4	0.01	1.3	0.86
LIFO	1	0.69	79.4	0.01	1.3	0.86
FIFO	2	0.74	80.6	0.06	4.5	0.91
LIFO	2	0.74	80.6	0.06	4.5	0.91
FIFO	3	0.82	82.1	0.14	6.4	0.99
LIFO	3	0.82	82.1	0.14	6.4	0.99
FIFO	4	0.91	83.5	0.23	8.3	1.08
LIFO	4	0.92	83.7	0.24	9.0	1.09
FIFO	5	1.03	85.2	0.35	10.9	1.20
LIFO	5	1.04	85.3	0.37	10.9	1.21

ACTUAL FORT ORD DATA

AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
0.63	66.0	0.12	3.8	0.96

TABLE 5. SIMULATION OF A BLOOD BANK USING FORT ORD DATA

BLOOD TYPE INPUT DATA TIME PERIOD

AB- Q INTERNAL =.187500 156 WEEKS
Q REQUIRED =.000001

SIMULATION RESULTS

POLICY	RATIO D/R	AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
FIFO	1	0.21	100.0	0.0	0.0	0.21
LIFO	1	0.21	100.0	0.0	0.0	0.21
FIFO	2	0.21	100.0	0.0	0.0	0.21
LIFO	2	0.21	100.0	0.0	0.0	0.21
FIFO	3	0.21	100.0	0.0	0.0	0.21
LIFO	3	0.21	100.0	0.0	0.0	0.21
FIFO	4	0.21	100.0	0.0	0.0	0.21
LIFO	4	0.21	100.0	0.0	0.0	0.21
FIFO	5	0.21	100.0	0.0	0.0	0.21
LIFO	5	0.21	100.0	0.0	0.0	0.21

ACTUAL FORT ORD DATA

AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
0.23	100.0	0.0	0.0	0.23

TABLE 6. SIMULATION OF A BLOOD BANK USING FORT ORD DATA

BLOOD TYPE   INPUT DATA   TIME PERIOD

O+   Q INTERNAL =.870647   156 WEEKS
Q REQUIRED =.856749

SIMULATION RESULTS

POLICY	RATIO D/R	AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
FIFO	1	1.87	25.3	0.58	12.2	7.34
LIFO	1	2.18	28.3	0.89	19.9	7.65
FIFO	2	3.19	36.5	1.94	19.2	8.66
LIFO	2	4.16	42.8	2.90	28.2	9.63
FIFO	3	5.29	48.6	4.07	26.3	10.76
LIFO	3	6.53	53.9	5.30	31.4	11.99
FIFO	4	7.78	58.0	6.58	28.8	13.24
LIFO	4	9.17	62.0	7.98	37.2	14.64
FIFO	5	10.42	64.8	9.26	32.1	15.89
LIFO	5	11.93	67.8	10.77	39.1	17.40

ACTUAL FORT ORD DATA

AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
3.00	31.8	2.65	63.0	9.39

TABLE 7. SIMULATION OF A BLOOD BANK USING FORT ORD DATA

BLOOD TYPE	INPUT DATA		TIME PERIOD
O-	Q INTERNAL	=.666667	156 WEEKS
	Q REQUIRED	=.646259	

SIMULATION RESULTS

POLICY	RATIO D/R	AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
FIFO	1	0.66	28.8	0.27	10.3	2.28
LIFO	1	0.73	30.9	0.34	14.7	2.35
FIFO	2	1.15	41.2	0.78	18.6	2.78
LIFO	2	1.43	46.5	1.05	26.3	3.05
FIFO	3	1.88	53.1	1.51	23.7	3.50
LIFO	3	2.21	57.1	1.85	27.6	3.83
FIFO	4	2.72	62.0	2.37	27.6	4.35
LIFO	4	3.08	64.8	2.73	31.4	4.71
FIFO	5	3.58	68.0	3.24	29.5	5.21
LIFO	5	3.98	70.2	3.64	35.3	5.60

ACTUAL FORT ORD DATA

AVERAGE UNITS OUTDATED PER WEEK	% OUTDATE	AVERAGE EXTERNAL SUPPLY PER WEEK	% TIME SHORT	AVERAGE NEW INVENTORY
1.06	36.2	0.92	34.6	2.92

TABLE 8. SIMULATION OF A BLOOD BANK USING FORT ORD DATA

LIST OF REFERENCES

[1] Drake, A.W., Keeney, R.L., Moorse, P.M., Analysis of Public Systems, M.I.T. Press, Cambridge, Mass., 1972. In particular Chapter 11, pages 216-234, by J.B. Jennings.

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d.	

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Approved for public release; distribution unlimited.

1. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Postgraduate School Monterey, California 93940

3. ABSTRACT

Blood bank operations of various hospitals in the Monterey area and the Red Cross Center in San Jose were studied, and as a result a simulation model is developed which is used to determine the effects on shortages and outdating of various operating policies in a given blood bank. Data from Fort Ord Hospital is used to illustrate the model. Specific results are discussed for a single blood type (A+), but the model can be used for all blood types. The model illustrates the difficulty of reducing both shortages and outdating simultaneously, but shows where this might be possible if certain operating policies are instituted.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Blood bank analysis						
Effects of shortages vs outdating						
Data base of 2988 units						
Analytic probability approach						
Simulation results						

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Blood bank analysis.